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Plains Hydrology And Reclamation Project: Investigation Of The Settlement Behaviour Of Mine Backfill

Heritage Fund

Alberta

LAND CONSERVATION AND
RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

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Report No. RRTAC 88-4

PLAINS HYDROLOGY AND RECLAMATION PROJECT:

INVESTIGATION OF THE SETTLEMENT BEHAVIOUR OF MINE BACKFILL

Compiled by
D.R. PAULS

Under Contract to Alberta Research Council

Prepared for
The Plains Coal Reclamation Research Program
of
THE LAND CONSERVATION AND RECLAMATION COUNCIL
(Reclamation Research Technical Advisory Committee)

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STATEMENT OF OBJECTIVE

The recommendations and conclusions in this report are those of the authors and not those of the Alberta Government or its representatives.

This report is intended to provide government and industry staff with up-to-date technical information to assist in the development of guidelines and operating procedures. The report is also available to the public so that interested individuals similarly have access to the best available information on land reclamation topics.

ALBERTA'S RECLAMATION RESEARCH PROGRAM

The regulation of surface disturbances in Alberta is the responsibility of the Land Conservation and Reclamation Council. The Council executive consists of a Chairman from the Department of Forestry, Lands and Wildlife. Among other functions, the Council oversees programs for reclamation of abandoned disturbances and reclamation research. The Reclamation Research Program was established to provide answers to the many practical questions which arise in reclamation. Funds for implementing both the operational and research programs are drawn from Alberta's Heritage Savings Trust Fund.

To assist in technical matters related to the development and administration of the Research Program, the Council appointed the Reclamation Research Advisory Committee (RRTAC). The Committee first met in March 1978 and consists of eight members representing the Alberta Departments of Agriculture, Energy, Forestry, Lands and Wildlife, Environment and the Alberta Research Council. The Committee meets regularly to update research priorities, review solicited and unsolicited research proposals, arrange workshops and otherwise act as a referral and coordinating body for Reclamation Research.

Additional information on the Reclamation Research Program may be obtained by contacting:

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RECLAMATION RESEARCH REPORTS

** 1. RRTAC 80-3: The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp.

DESCRIPTION: This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.

** 2. RRTAC 80-4: Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi, and H.F. Regier. 160 pp.

DESCRIPTION: Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.

N/A 3. RRTAC 80-5: Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker, and P.F. Polster. 2 vols, 541 pp.

DESCRIPTION: Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their fitness for use in Reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.

N/A 4. RRTAC 81-2: 1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp.

DESCRIPTION: This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.

N/A 5. RRTAC 81-3: Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stien, R. Leitch, and G. Lutwick. 253 pp.

DESCRIPTION: Presents nine technical papers on the chemical, physical and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites and use of ash as a soil amendment. Workshop discussions and summaries are also included.

N/A 6. RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp.

DESCRIPTION: Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system. Vol. 2 comprises the keyword index and computer access manual.

N/A 7. RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology and Groundwater. C.B. Powter and H.P. Sims. 97 pp.

DESCRIPTION: This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available from the Alberta Environment Library.

N/A 8. RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp.

DESCRIPTION: Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials.

N/A 9. RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp.

DESCRIPTION: Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

N/A 10. RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz. 123 pp.

DESCRIPTION: Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics and resulting water quality. Mitigative measures and priorities were also discussed.

N/A 11. RRTAC 83-5: Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp.

DESCRIPTION: This is a review and analysis of information on planting stock quality, rearing site preparation, planting and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.

*** 12. RRTAC 84-1: Land Surface Reclamation: A Review of International Literature. H.P. Sims, C.B. Powter, and J.A. Campbell. 2 vols, 1549 pp.

DESCRIPTION: Nearly all topics of interest to reclamation including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.

** 13. RRTAC 84-2: Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp.

DESCRIPTION: This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.

* 14. RRTAC 84-3: Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results and expenditures.

** 15. RRTAC 84-4: Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser, and J.C. Zak. 2 vols, 676 pp.

DESCRIPTION: This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symboints in various amended spoil types.

** 16. RRTAC 85-1: Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz. 416 pp.

DESCRIPTION: Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

* 17. RRTAC 85-2: Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results and expenditures.

** 18. RRTAC 86-1: A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp.

DESCRIPTION: The report examines the critical issue of settling pond design and sizing and alternative technologies.

** 19. RRTAC 86-2: Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp.

DESCRIPTION: Reconstructed soils representing different materials handling and replacement techniques were characterized and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.

* 20. RRTAC 86-3: Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp.

DESCRIPTION: In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

** 21. RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp.

DESCRIPTION: This report summarzies the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

** 22. RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Program. A. Maslowski-Schutze. 71 pp.

DESCRIPTION: This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

* 23. RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp.

DESCRIPTION: The report deals with the availability of water supply in or beneath cast overburden at the Battle River Mining area in east-central Alberta to support post-mining land use. Both groundwater quantity and quality are evaluated.

* 24. RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp.

DESCRIPTION: This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

* 25. RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results and expenditures.

** 26. RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp.

DESCRIPTION: This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed.

** 27. RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp.

DESCRIPTION: Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual included provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

** 28. RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik, and D.G. Walker. 174 pp.

DESCRIPTION: This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area.

** 29. RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (compiler). 218 pp.

DESCRIPTION: Technical papers were presented which describe: the mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

* 30. RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results and expenditures.

* 31. RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp.

DESCRIPTION: The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the east slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed.

** 32. RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp.

DESCRIPTION: The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions.

* 33. RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp.

DESCRIPTION: The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials

were set up near the Vesta mine in East Central Alberta using ash readily available from nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

* 34. RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp.

DESCRIPTION: This report describes a study to evaluate the influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

** 35. RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Area. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp.

DESCRIPTION: This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

** 36. RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus maps.

DESCRIPTION: The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands

adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. A series of maps supplement the report.

** 37. RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp.

DESCRIPTION: The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

** 38. RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp.

DESCRIPTION: This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

* 39. RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp.

DESCRIPTION: This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

** 40. RRTAC 88-1: Eccles, T.R., R.E. Salter and J.E. Green. A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. 101 pp. plus appendix.

DESCRIPTION: The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be used by site operators and reclamation officers.

** 41. RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (Compiler). Alberta Land Conservation and Reclamation Council Report #RRTAC 88-2. 135 pp.

DESCRIPTION: Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation.
The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

** 42. RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp.

DESCRIPTION: The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their uninoculated counterparts.

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PREFACE

This volume is part of a series of reports that presents the findings of the Plains Hydrology and Reclamation Project (PHRP), an interdisciplinary study that focuses primarily on hydrologic aspects of the reclamation of surface coal mines in the Plains of Alberta. This research has been conducted by the Alberta Research Council, as part of the Alberta Government's Reclamation Research Program. The program is managed by the Land Conservation and Reclamation Council and is supported by the Heritage Trust Fund.

The focus of the PHRP is to develop a predictive framework that will permit projection of success for reclamation and impact of mining on water resources on a long-term basis. The predictive framework is based on an understanding of processes acting within the landscape so that, in the future, mine sites that are not totally analogous to those that have been studied can be evaluated as well.

The project involves a holistic approach to reclamation by integration of studies of geology, hydrogeology, and soils, not only in the proposed mining area, but also in the adjoining unmined areas. This approach permits the assessment of impacts and of long-term performance, not only in reclaimed areas, but also in the surrounding area.

The research of the PHRP was directed toward the following two major objectives and eight subobjectives.

Objective A

To evaluate the potential for reclamation of lands to be surface mined. The focus is on features of the landscape that make it productive in a broad sense not restricted to revegetation. This objective was organized into five subobjectives.

1. To assess and evaluate the potential for long-term degradation of reclaimed soils through salt build-up.
2. To assess and evaluate the effectiveness of topographic modification and selective placement of

materials to mitigate deleterious impacts on chemical quality of groundwater.

3. To assess the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations.
4. To evaluate the productivity potential (capability) of post-mining landscapes and the significance of changes in capability as a result of mining.
5. To assess and evaluate limitations to post-mining land use posed by physical instability of cast overburden.

Objective B

To evaluate the long-term impact of mining and reclamation on water quantity and quality. This objective was organized into three subobjectives.

1. To assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products.
2. To assess and evaluate infiltration, groundwater recharge, and groundwater-surface water interactions within cast overburden.
3. To characterize the groundwater chemistry generated within cast overburden.

Studies directed at these objectives began in 1979 at the Battle River site in east-central Alberta. Work began in 1982 at a second study area at Highvale Mine south of Lake Wabamun.

This volume presents part of the project findings related to Subobjective A-5, the assessment of potential deterioration of reclaimed landscapes as a result of surface instability. The settlement study, which has been conducted by researchers at the Civil Engineering Department of the University of Alberta, under

contract to the Research Council, covers both field and laboratory aspects of differential subsidence in reclaimed landscapes.

The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests" covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil.

Field observations of subsidence features noted the rapid appearance of depressions and sinkholes following a very wet spring and early summer in 1982. In addition, monitoring of extensometers and groundwater levels, which began in 1979, indicated that maximum compression occurred just above the rising groundwater level. These observations led to the conclusion that resaturation of the spoil plays a major role in the subsidence process. The research described in this report was initiated to examine this phenomenon.

The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta" describes a series of laboratory tests that have been used to determine the behavior of overburden materials when brought into contact with water. Field evidence, which is presented elsewhere in project reports, demonstrates that surface subsidence is directly related to wetting of the spoil material. It was hoped that the static slaking tests described in this report could be used to classify the overburden in terms of its tendency to produce subsidence of the final spoil surface. Results of this study, however, indicated that variability is so great within the overburden that no such classification is possible.

The report entitled "Classification System for Transitional Materials: Plains Region of Alberta" describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta. The unique properties of these materials are responsible for the settlement behavior of the spoil.

ACKNOWLEDGEMENTS

Funding for the Plains Hydrology and Reclamation Project comes from the Alberta Heritage Savings Trust Fund, administered by the Land Conservation and Reclamation Council. The use of the facilities and the support of the Departments of Civil Engineering and Mineral Engineering of the University of Alberta are greatly valued. Drs. Dusseault and Scott were funded by the Alberta Oil Sands Technology and Research Authority during this period, and much of the data herein are applicable to the concepts of oil sands overburden removal. The co-operation of mine personnel and members of the Alberta Research Council is appreciated.

Report 1: SIMULATION OF MINE SPOIL SUBSIDENCE BY CONSOLIDATION TESTS

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ABSTRACT

This document has been prepared as a final report on the analyses of the Laboratory Consolidation Test Program that were carried out under the PHRP at the University of Alberta during 1982. The object of this program of tests was to simulate the subsidence that occurs in newly reclaimed mine spoil in order to better understand the mechanisms of subsidence phenomena.

A series of large diameter consolidation tests were performed on spoil from the Vesta Mine site located near Forestburg, Alberta. The spoil samples were considered representative of the overburden handled at the Vesta Mine, a heterogeneous mixture of medium soft dark grey clay, hard shale lumps, light grey clayey sand, and weakly cemented clayey sandstone. For the purposes of simulation, samples consisted of various particle sizes ranging from soil grains to 30 mm lumps.

The laboratory program consisted of a series of ten tests. The samples were placed in an oedometer and subjected to loads ranging from 25 kPa to 460 kPa to simulate settlement under overburden loads. After stabilizing under the maximum test load, the sample was exposed to a resaturation fluid, which was either distilled water or groundwater taken from Alberta Research Council wells located on mine property to simulate saturation of the spoil by surface infiltration or by rise of the groundwater table.

The reaction of the sample when resaturated is of special interest to the project. Field observations have indicated that the presence of a resaturation fluid dramatically accelerates the consolidation process. This was also demonstrated by the test results. Even under loads of 300 to 460 kPa, the samples tested underwent a significant amount of vertical strain when the resaturation fluid was first introduced. It is also notable that although the consolidation that took place on resaturation occurred rapidly, resaturation fluid was continually absorbed into the sample at an appreciable rate for a long period of time.

The major conclusions of the study are as follows:

1. The salinity of the resaturation fluid has no effect on the amount or rate of settlement.
2. Resaturation destroys lump effective stress, causing collapse of the microporosity as well as swell/slake deterioration of lumps.
3. Resaturation settlement is rapid once water is available, but water intake is slower than vertical deformation rate.
4. Long-term consolidation continues well after resaturation, but at a significantly reduced rate.

1. INTRODUCTION

The primary goal of the overall PHRP settlement study is to investigate the parameters that influence the amount and distribution of ultimate subsidence of newly reclaimed mine spoil in prairie coal strip mines and to determine methods to mitigate such behavior in the backfill material. In newly reclaimed areas at Diplomat and Vesta Mines, the subsidence can be easily seen in the field and became especially obvious during the growing season of 1982 when numerous bowls and sinkholes formed on this land at Diplomat Mine. The above-average snowmelt and rainfall in the area immediately preceding and during the period are believed to be related to the subsidence. Although this problem may be only a small proportion of the overall concerns relating to the reestablishment of land productivity, it has a significant impact on the economics and planning of reclamation schemes. For example, because of the distinct undulating surface of the reclaimed land north of the Battle River near Forestburg, the productive capability of the as built reclaimed surface is degraded relative to the intended reclaimed surface in two ways:

1. By adding physical obstacles, such as ponded water, to be dealt with in the cultivation process.
2. By increasing potential salt contamination of the topsoil as a result of evaporation of standing water in the depressions; it should be noted that even with the differential settlement, the reclaimed surface contains less area of water holding depressions than the premining surface.

To help establish land use parameters, several instrumented sites have been installed on the Diplomat Mine site and the Vesta Mine site for long-term monitoring (Dusseault et al. 1983b). These sites have provided field data to quantify the amount and rate of the subsidence.

To complement the field data, two extensive laboratory programs have been conducted to date. A Slake/Swell Test Program was

performed on overburden samples from the Vesta Mine site. This program has been covered in a separate report. The second laboratory program, a Consolidation Test Program, was conducted in 1982 to model the behavior of cast-back overburden under conditions of overburden stress and groundwater resaturation. The latter program is discussed below.

The usual stress change occurring in the field after disaggregation of the overburden by mining and casting is one of monotonically increasing normal stress until the total overburden load is imposed. At some later date, the surface is levelled, which represents only a minor redistribution of stresses. Zones of compaction are produced in the spoil piles and under haul roads. After the topsoil has been replaced, the ground surface is left untouched, and no load change takes place. With time, the groundwater level will rise and saturate the material.

Field sites have been observed for 42 months to date. Both the instrument data and visual observations of the ground surface indicate little long-term subsidence occurs after spoil pile levelling until resaturation takes place. The effect of resaturation is to destroy the moisture suction that exists in cast-back lumps, and to provide water for slaking and swelling. The laboratory test program was designed to follow this stress pattern as closely as possible in an attempt to simulate field behavior.

There was not an attempt made to simulate other spoil conditions such as density and lump size and distribution. The effect of water on spoil under similar stress conditions as in the field, was the emphasis of the modelling. Examining the stress/strain relationship of the spoil materials and quantitatively simulating subsidence through inundation by controlling sample conditions either by obtaining undisturbed spoil samples or by remolding samples to field conditions is much more difficult. Undisturbed samples of spoil are difficult to obtain since the in situ density is variable and low density spoil is compacted as it is pushed into a sample tube. Remolding spoil is also difficult because

the compacted character of the in situ spoil is not known except indirectly through density measurements, which is greatly variable. The random distribution of settlement features on the landscape with a preference for windrow valley locations, suggest that settlement occurs from loosely placed spoil. Therefore the procedure was chosen to place spoil into a sample cell in a loose condition with lumps and matrix material making up the sample and simulate overburden stress and inundation of loosened material.

The program for the ten consolidation tests has been outlined in Table 1. The final confining pressures range from 25 kPa to 460 kPa. These pressures represent overburden depths of approximately 1.2 to 23 m. This is considered to be a sufficient range of settlement pressures as the maximum depth of overburden that has been encountered in this study is approximately 18 m.

After the compression was essentially complete under the final test pressure, the sample was resaturated. For each maximum test pressure, two resaturation fluids were used - distilled water and groundwater taken from wells on the Vesta Mine site. This was done to measure any difference in subsidence when mine spoil is resaturated with rainwater or groundwater.

Table 1. Consolidometer test program.

Test	Load Sequence to Resaturation	Resaturation Fluid
25A	0 - 25 kPa - Resaturation	distilled water
25B	0 - 25 kPa - Resaturation	ground water
75A	0 - 25 - 75 kPa - Resaturation	distilled water
75B	0 - 25 - 75 kPa - Resaturation	ground water
150A	0 - 50 - 100 - 150 kPa - Resaturation	distilled water
150B	0 - 50 - 100 - 150 kPa - Resaturation	ground water
300A	0 - 100 - 200 - 300 kPa - Restauration	distilled water
300B	0 - 100 - 200 - 300 kPa - Restauration	ground water
460A	0 - 150 - 300 - 460 kPa - Resaturation	distilled water
460B	0 - 150 - 300 - 460 kPa - Resaturation	ground water

2. MATERIAL PROPERTIES

Spoil samples were collected from the Vesta Mine site. Index data and x-ray diffraction clay mineralogy were collected for the samples. The procedures used to collect this data are similar to those used by Maslowski Schutze et al. 1986. Tables 2 and 3 contain clay mineralogy, Atterberg Limits, and groundwater chemistry data.

There are two distinctive spoil types in the Battle River mine area; spoil derived from normally consolidated glacial till and spoil derived from highly overconsolidated smectitic bedrock. The spoil tested in this program was made up predominantly of bedrock derived spoil although some brownish coloured spoil samples indicate that a mixture containing till derived spoil was also likely sampled.

The uniformity of material for all samples shown by liquid limits ranging only from 72% to 82% is surprising because liquid limits ranging from 50% to 200% for bedrock type spoils and ranging from 27% to 33% for till type spoils is more indicative of materials in the Battle River Mine area.

Table 2. Atterberg limits and clay mineralogy. The spoil material is composed of approximately a 30/30/40 ±10%, clay/silt/sand mix.

Test	Liquid Limit (%)	Plastic Limit (%)	Montmorillinite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)
25A and B	73	25	80	10	>5	>5
75A and B	78	23	95	5	trace	trace
150A and B	72	24	95	5	trace	trace
300A and B	72	26	80	10	>5	>5
460A and B	82	23	80	10	>5	>5

Table 3. Groundwater chemistry (ppm).

Test	Calcium	Magnesium	Sodium	Potassium	Carbonate	Bicarbonate	Sulphate	Chloride
25, 75, 150	311	62	2375	23	0	1418	5240	12
300, 460	313	55	931	8	0	415	2605	3

3. LABORATORY PROCEDURE

3.1 TEST EQUIPMENT

The basic testing cell is a 250 mm high by 300 mm diameter cylindrical consolidometer lined with teflon to minimize side friction. Figure 1 is a schematic of the consolidation cell. For all tests, an air controlled Bellofram was used for loading. An LVDT was used to measure vertical settlement of the sample with time. The strain data were collected by an electronic data acquisition system and plotted by computer. The resaturation water was added from a calibrated reservoir that was connected to the porous stone at the base of the sample.

3.2 SAMPLE ASSEMBLY

Mined, but otherwise intact spoil material was obtained from Diplomat and Vesta Mine sites. At the time of collection, the spoil had been in place for approximately three months. The sample was placed in a sealed container to ensure no further moisture loss and carefully transported and stored to ensure no further disaggregation took place.

3.3 TEST PROCEDURE

In the laboratory, a blend of material was placed loosely in the cell to a depth of approximately 150 mm. The load cap (1 kPa) was placed in the cell and the initial height of the specimen measured. The desired simulated overburden load was placed on the unsaturated sample in the cell, and the vertical strain was monitored. The load was stepped up to the maximum test pressure in increments as outlined in Table 1. Each successive load increment was applied after the sample had shown stabilization from the previous load.

Resaturation was achieved by introducing from the base, a fluid corresponding to either distilled water or groundwater. The chemistry of the groundwater used has been summarized in Table 3.

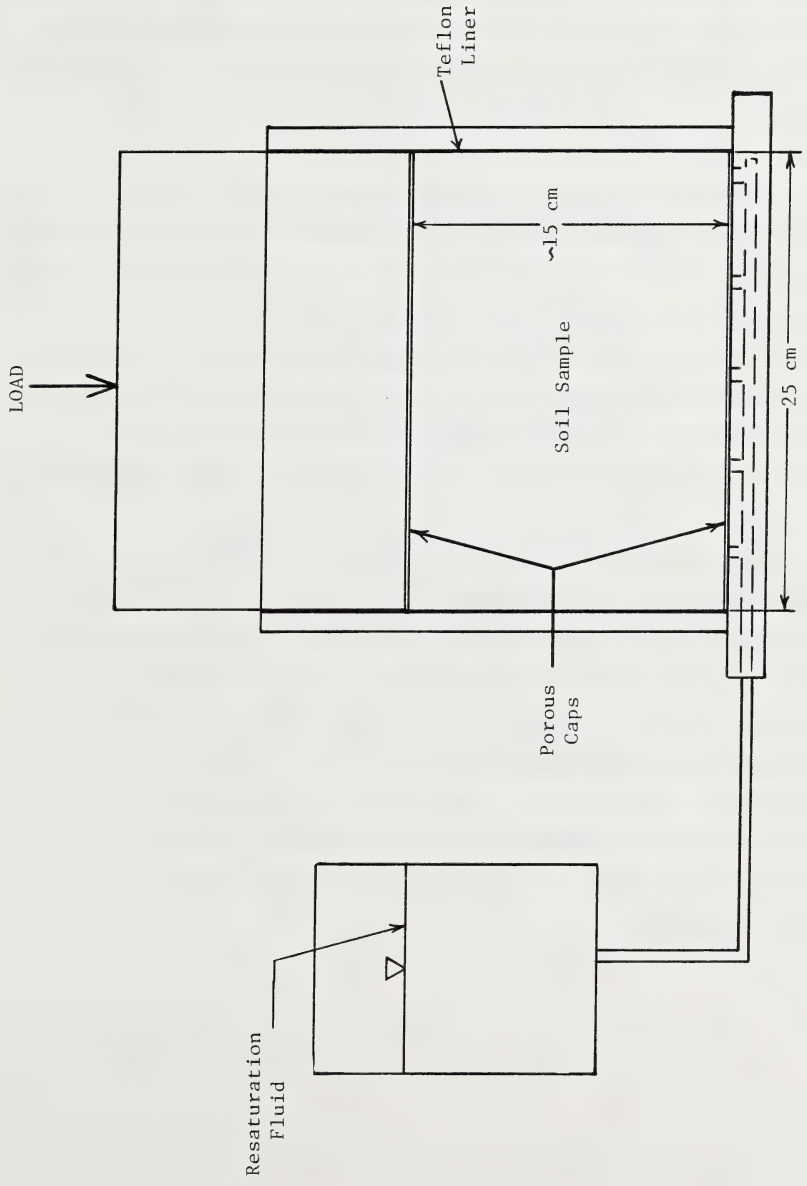

Figure 1. Consolidation apparatus.

The resaturation fluid was maintained from a reservoir that was kept at the same elevation as the top of the sample. Two measurements were taken: One was the vertical settlement over time on the sample; the other was the volume of water absorbed as a function of time.

Upon completion of the tests, the sample was removed and weighed for calculation of final moisture content and degree of saturation. Table 4 contains detailed geomechanical data from the ten tests. The table, however, displays some inconsistencies. Final saturation values greater than 100% are recorded and the void ratios back calculated from the dry mass do not correspond uniquely with the void ratios back calculated from final moisture contents and saturations. This is due in part to experimental error, but mainly to heterogeneity of the spoil, which can contain coaly fragments or masses of siderite. A specific density of 2.65 was assumed for calculations. The data are to be interpreted as trends rather than absolute values.

Some investigation was carried out to determine an appropriate period of time necessary for a test. In each stage, it was found that a significant amount (about 80%) of settlement occurs in the first several hours after applying a load increment or resaturating a sample. A long-term (28-day) test was conducted, but the settlement curve showed no deviation from a gradually levelling settlement trend. As a result, the consolidation tests were run in a compressed time period; that is, the next successive stage in the test was implemented shortly after the sample had undergone its significant settlement.

Table 4. Summary of consolidation test results.

Test	Moisture Content %		Void Ratio		Degree of Sat %		Sample Height (cm)		Unit Strain %	Water Absorbed (liters)	Dry Mass (kg)
	Initial	Final	Initial	Final	Initial	Final	Initial	Final			
25A	22.4	29.9	1.60	0.94	39	89	10.04	7.49	24.5	1.315	7.83
25B	17.9	36.5	1.91	1.45	26	70	12.30	10.35	15.9	1.640	8.57
75A	22.0	30.3	1.61	1.08	38	78	14.80	11.80	20.3	0.945	11.51
75B	24.6	31.2	2.06	1.16	33	75	15.63	8.02	29.6	1.015	10.31
150A	16.4	26.2	2.29	0.75	20	99	15.00	7.96	46.9	0.940	9.25
150B	15.6	24.6	2.00	0.66	22	102	14.30	7.92	44.7	0.875	9.65
300A	24.1	29.6	1.98	0.71	34	115	16.50	9.49	42.5	0.670	11.24
300B	18.7	24.7	2.01	0.64	26	107	16.10	8.75	45.7	0.720	10.83
460A	16.2	18.2	2.03	0.56	22	87	17.30	9.23	46.6	0.240	11.85
460B	17.2	19.7	1.92	0.49	25	111	17.00	8.65	49.1	0.310	11.78

4. TEST RESULTS

The settlement curves for the tests have been plotted in Figures 2 to 6. There are two tests shown on each plot. Both tests on each plot have an identical test sequence but have been resaturated by groundwater or by distilled water.

The curves on each plot are similar. This would indicate that the difference between resaturation with groundwater and resaturation with distilled water is not enough to produce significantly varying amounts of settlement. Although the shape of the curves tends to be similar, their vertical position on the graph varies. This variation in vertical position indicates that the samples have settled different amounts, generally in the first loading increment. This is partially attributable to the different void ratios at which the samples were placed. In Figure 3, the settlement curves for tests 75A and 75B especially reflect the difference in initial void ratio. Test 75B, which shows a much greater initial settlement than 75A, has an initial void ratio of 2.06 as compared with an initial void ratio of 1.61 for test 75A. At the other extreme, tests 460A and 460B, which closely follow the same settlement path, have similar initial void ratios of 2.03 and 1.92, respectively. It is also notable that after each load increment or resaturation stage, approximately 80% to 90% of the settlement occurs in the first 2 or 3 h.

Figure 7 illustrates the relationship between total stress on the sample and the change in void ratio for each loading step for all tests. Although the variation in initial void ratio introduces some spread in the results, the settlement trend for this mine spoil is well shown.

Figures 8 to 12 illustrate the rate of water absorption as compared with the change in void ratio for the test series. Here again, as with the settlement curves, two tests have been plotted on each graph. The confining stress for each sample is the same: The two curves represent a different resaturation fluid. These plots show clearly that, although the settlement stabilizes rapidly after

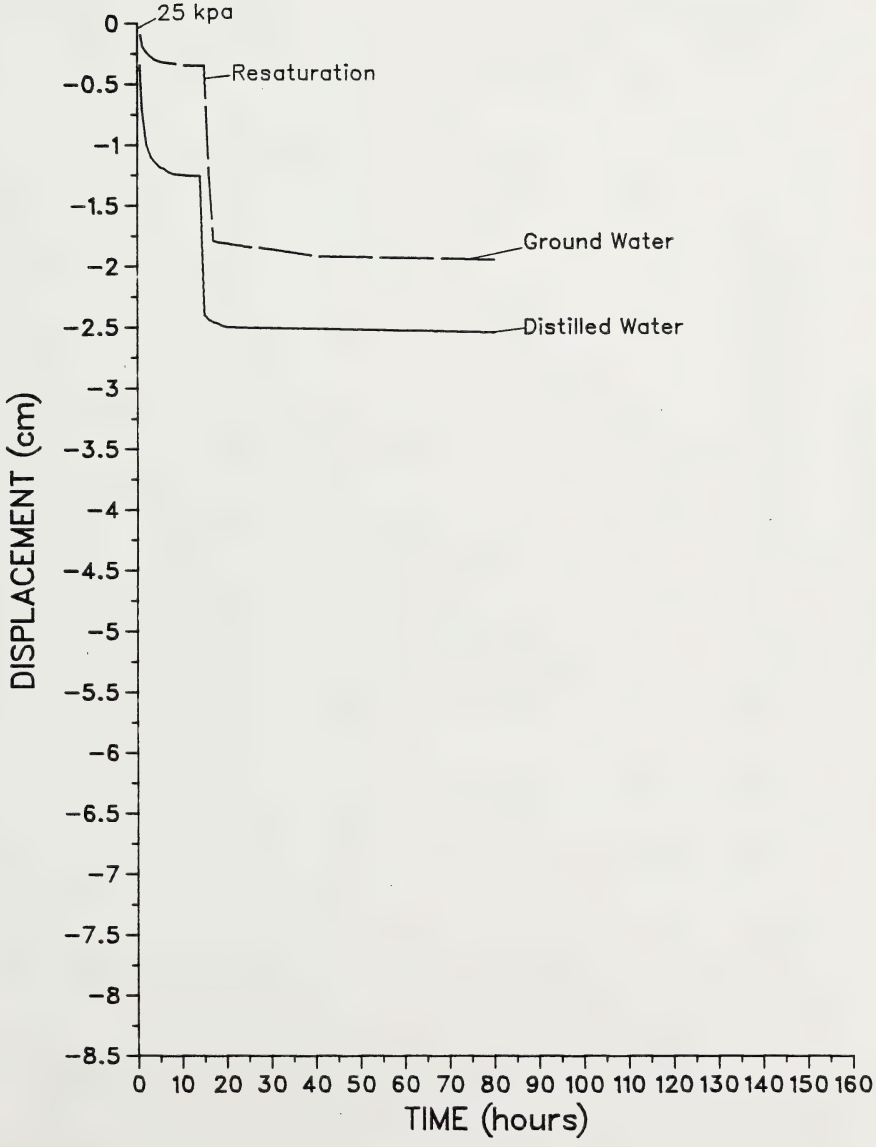

Figure 2. Consolidation curves, 25 kPa tests.

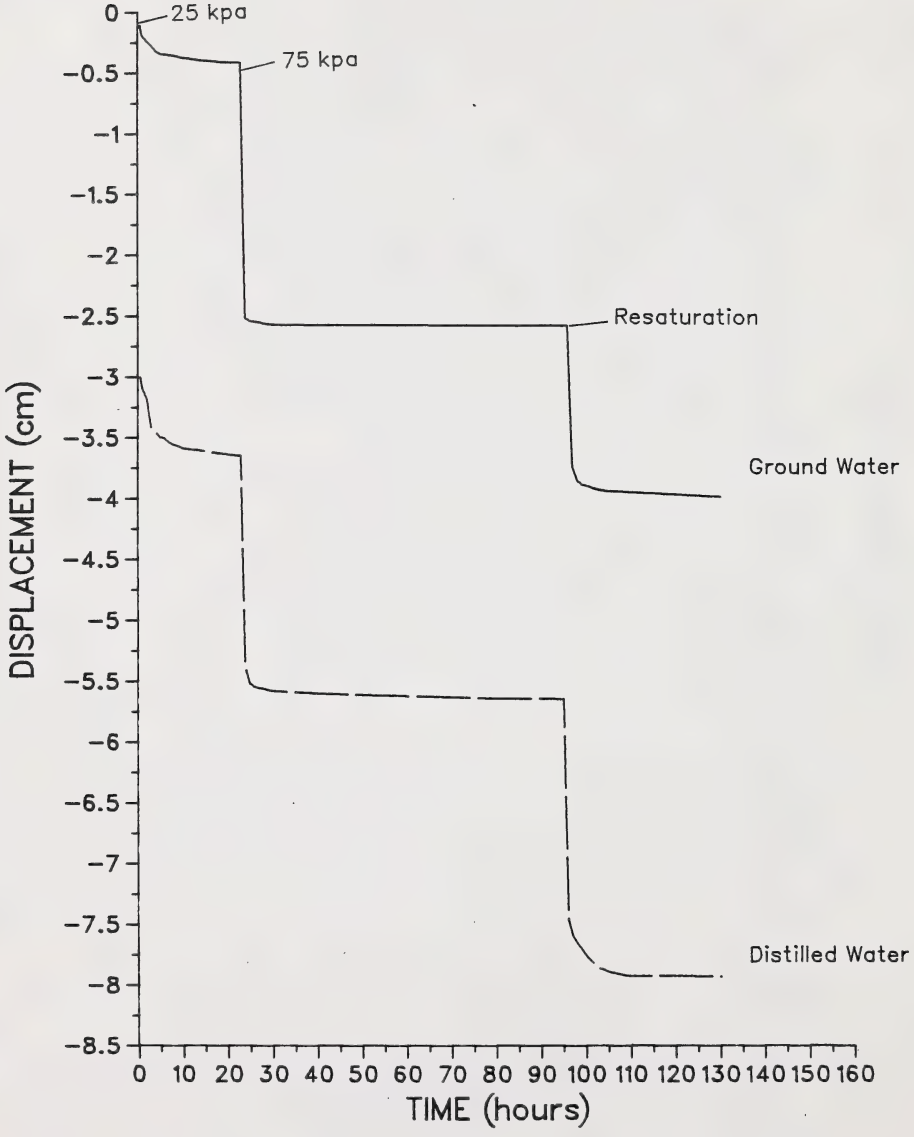

Figure 3. Consolidation curves, 75 kPa tests.

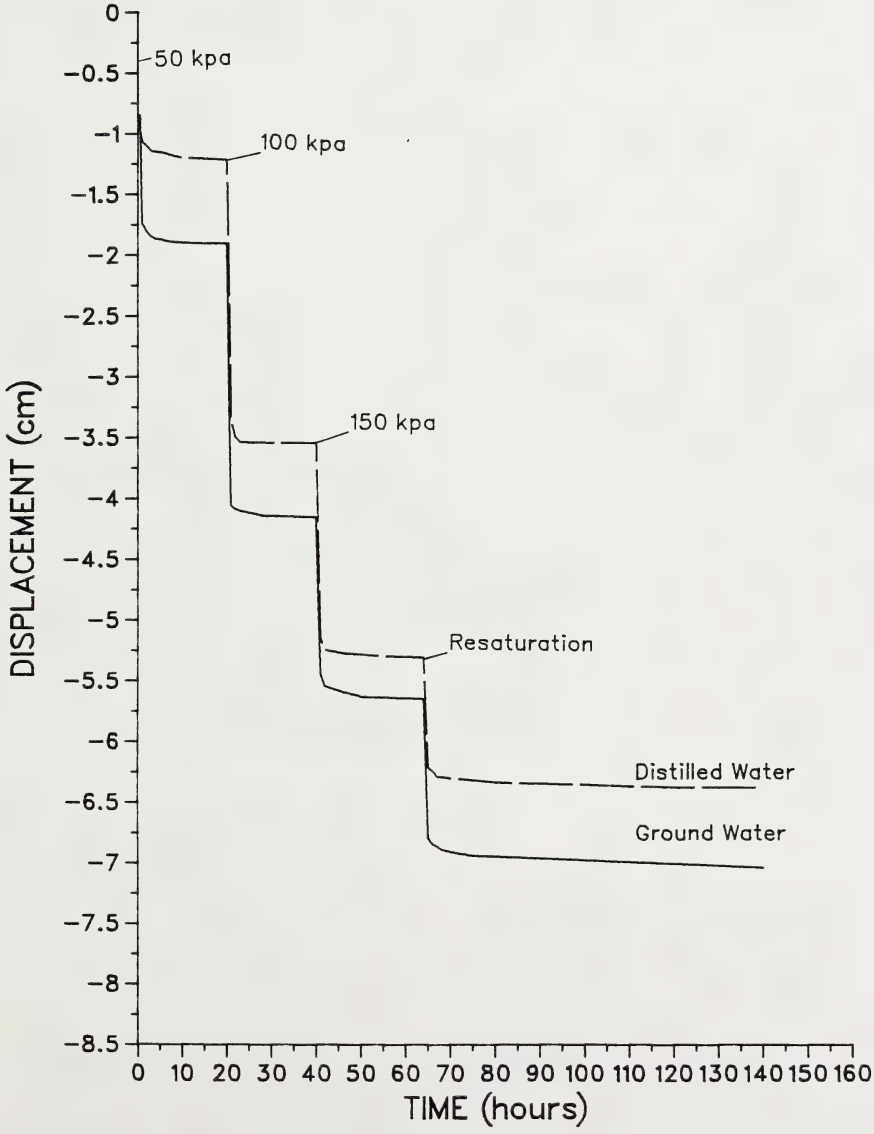

Figure 4. Consolidation curves, 150 kPa tests.

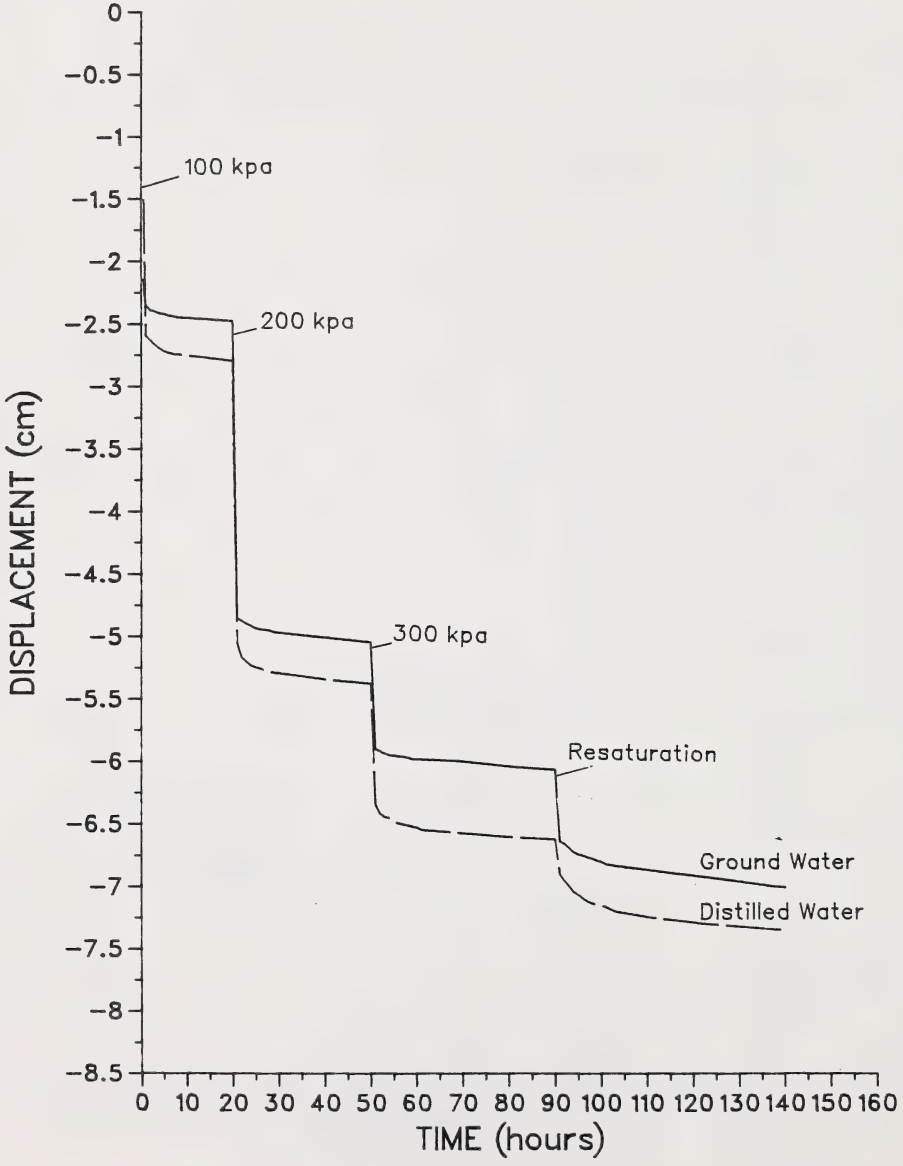

Figure 5. Consolidation curves, 300 kPa tests.

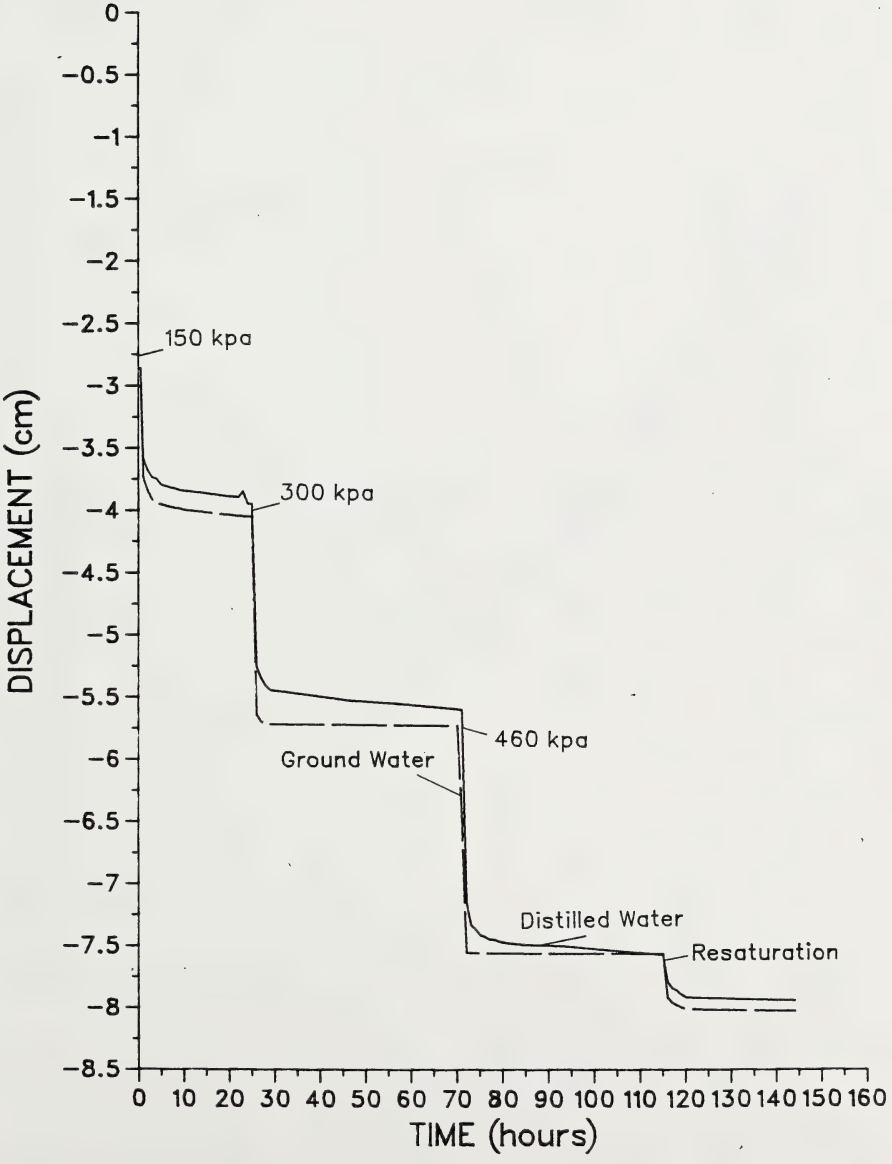

Figure 6. Consolidation curves, 460 kPa tests.

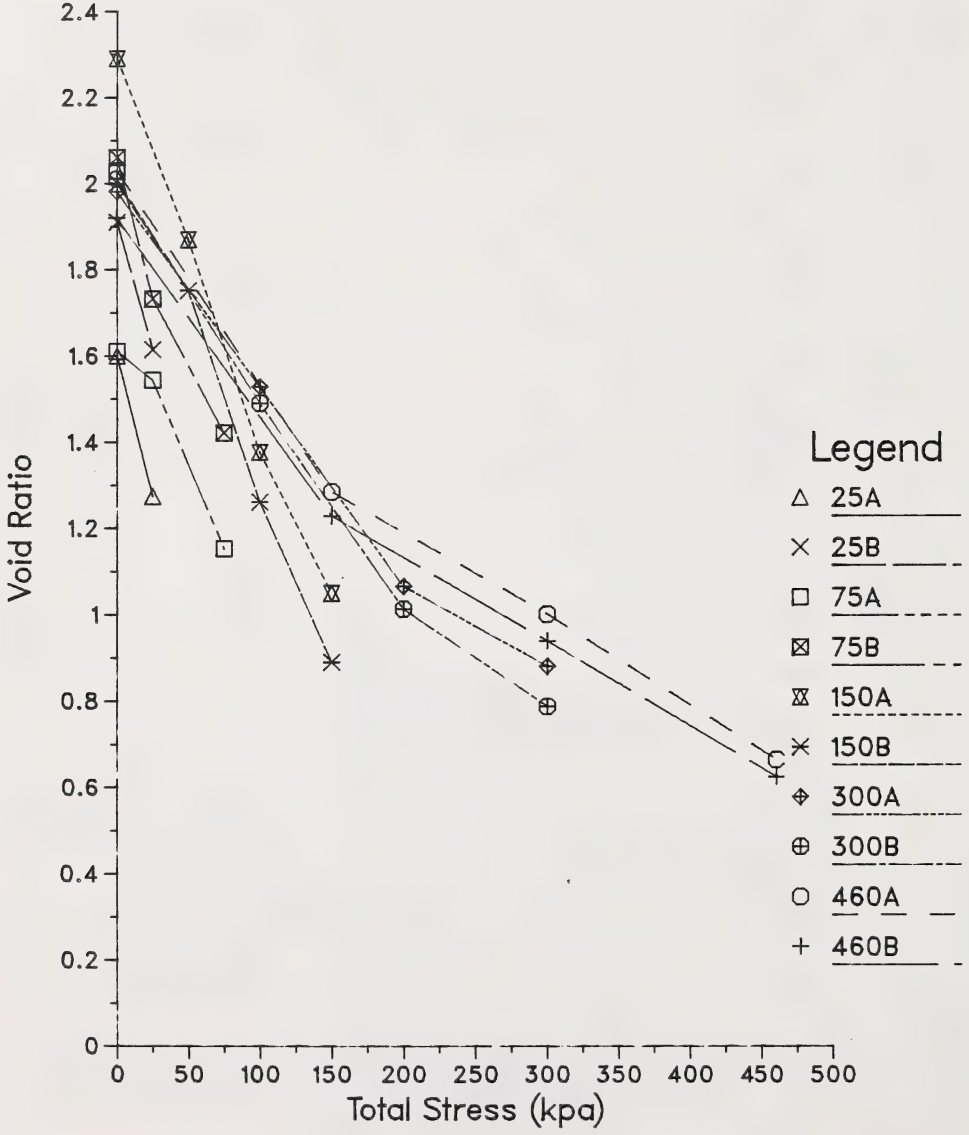

Figure 7. Void ratio/total stress relationships.

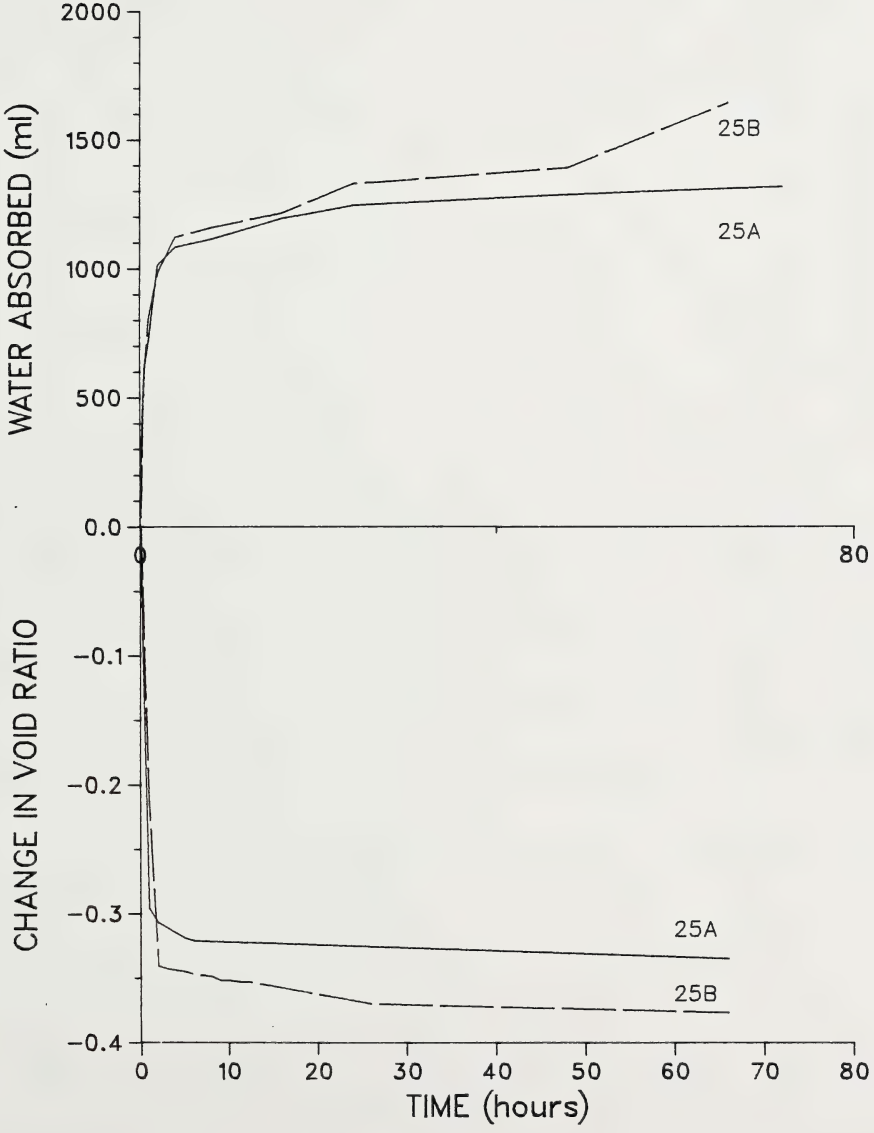

Figure 8. Comparison of water intake and vertical strain during resaturation, 25 kPa tests.

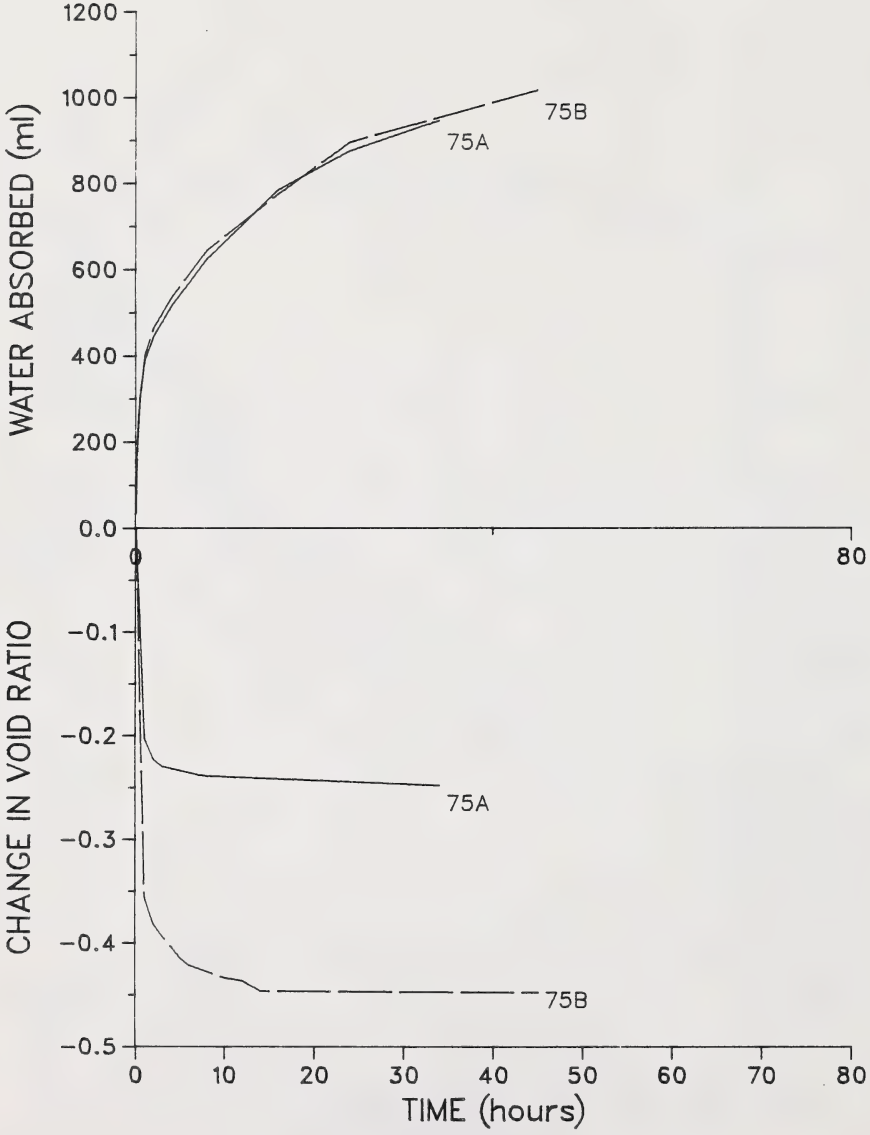

Figure 9. Comparison of water intake and vertical strain during resaturation, 75 kPa tests.

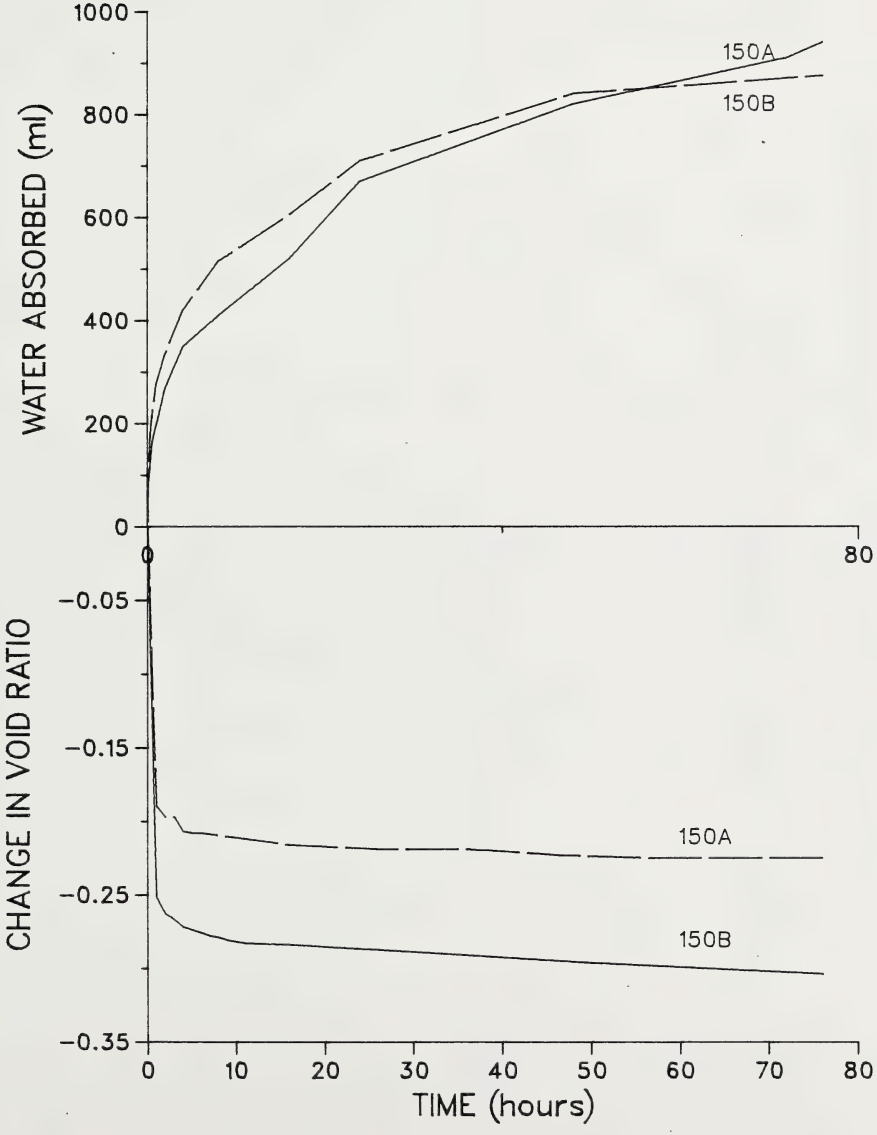

Figure 10. Comparison of water intake and vertical strain during resaturation, 150 kPa tests.

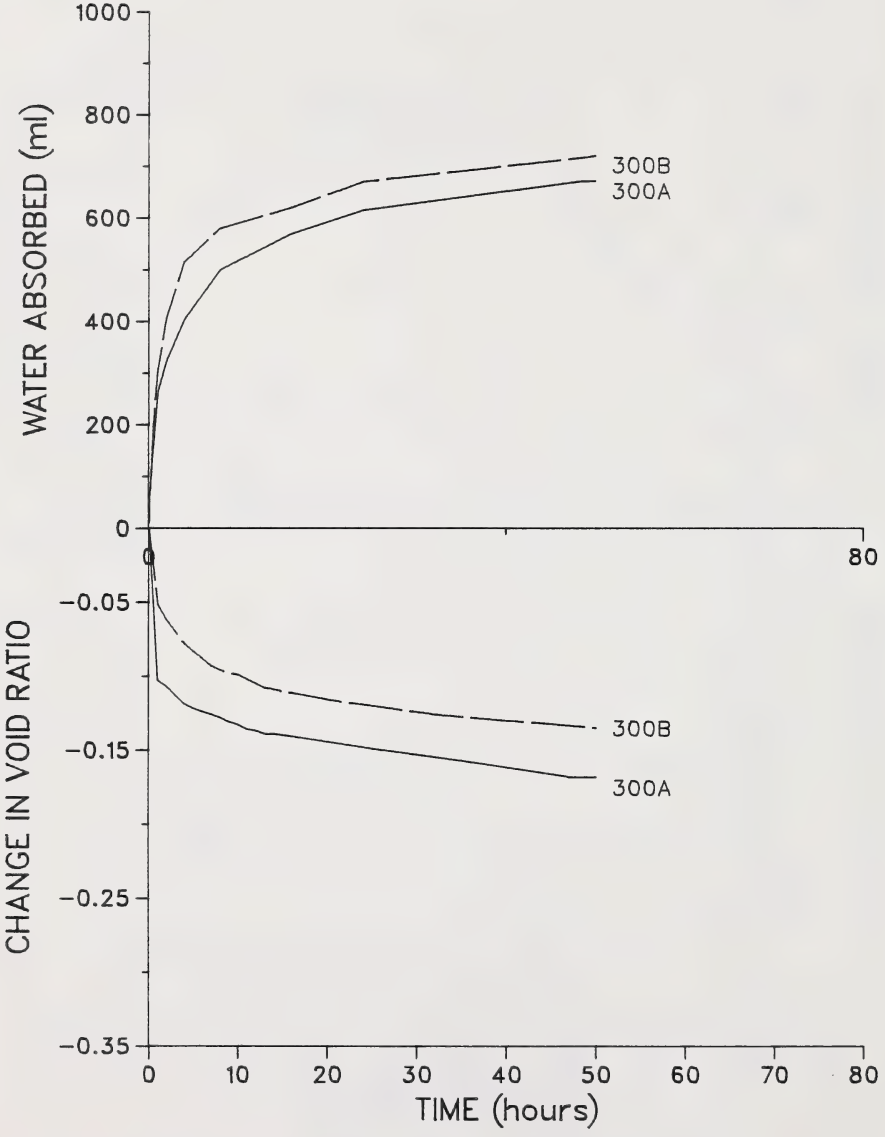

Figure 11. Comparison of water intake and vertical strain during resaturation, 300 kPa tests.

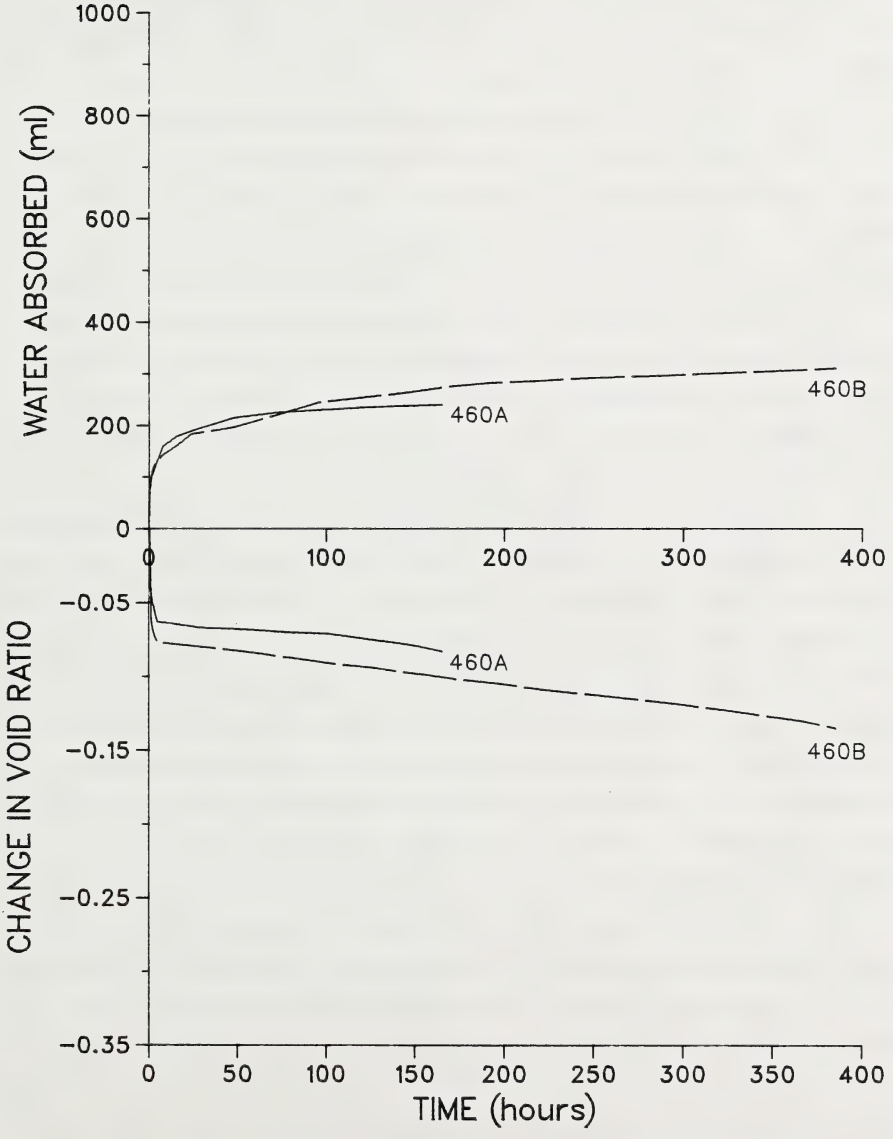

Figure 12. Comparison of water intake and vertical strain during resaturation, 460 kPa tests.

resaturation, resaturation fluid continues to be absorbed at a slower rate.

For the most part, the curves for both samples on a plot are the same. That is, the resaturation fluid used appears to make little difference in the amount absorbed or the time required to absorb the fluid.

Figure 12, which describes water absorption trends for tests 460A (distilled water) and 460B (groundwater), illustrates the rate of water absorption for long-term tests. Test 460B, which was conducted for over 20 days, showed that water was still being absorbed at the end of the test. The water absorption curves for tests 25A and 25B (Figure 8) show that most of the water absorption was complete in 30 h. This relatively short period of time for stabilization of absorption can be expected as the void ratio for these samples subjected to only a small load is higher than the rest of the samples, allowing for a higher permeability.

Barden et al. 1973 also describe the collapse mechanisms in partly saturated soils. He points out three forms of interparticle bonding which are destroyed with moisture. The first form of bonding is through flocculation of clay particles deficient of moisture forming clay buttresses between larger silt and sand particles. When free moisture is introduced to the soil, the clay deflocculates and the buttresses are eroded. Another form of bonding is through soluble chemicals collecting and hardening between larger particles, acting as a cement. Moisture entering the soil through a resaturation process dissolves the deposits and the soil looses strength. The third type of bonding occurs because of the unsaturated, expanded condition of the spoil. The small voids of the material became partially filled with water as the material is unloaded. The tight curvature of the water surface exerts negative pores pressures between grains thus bonding the material. The almost immediate collapse of the spoil from Diplomat Mine upon inundation and the observed suction capacity of the unsaturated spoil suggests the importance of capillary action in this spoil. The slow rate of

collapse, negligible suction capacity and the grain size distribution of the smectitic bedrock spoil suggests that a proportion of bonding of the other two forms may also govern the behavior of the spoil from Vesta and Paintearth Mines, but bedrock type spoil cannot be considered as a classical collapsing soil structure.

There is also a fourth collapse mechanism which is an extension of these models to include settlement from macroporosity. All of these authors' models are micromodels, and are attempts to explain hydrocompaction of soils which are loose at grain-to-grain scale. The settlement at Diplomat Mine and particularly at Vesta Mine is more likely the result of a macroscopic process on the scale of centimetres. Individual lumps of clay shale are very strong because of the high negative pore water pressures which develop during mining and disturbance of the clay shales and sandstones, and because of the highly overconsolidated state of the overburden and low natural water content relative to the plastic limit of the clay materials. The intraclast porosity, as measured by bulking, is from 20 to 30%. When water is available, negative pore pressures are destroyed, clay particles are dispersed, and chemical bonds eroded. The lump cannot collapse until it has been weakened as it absorbs water to cause a reduction of all types of bonding. Then it will swell, slake and deform to fill the surrounding void space. If the amount of swell under the overburden pressure is large, subsidence will be small. However, if the large lumps do not swell, or swell initially and then consolidate under the overburden pressure, surface subsidence could be considerable. An insufficient data base exists to quantify this process for the spoil from Vesta Mine, but an important point is that the mechanisms are different for mine spoil than those identified for homogeneous or naturally occurring collapsing soils. These ideas are explained further by Dusseault et al. (1985).

Figures 8 to 12 indicate that the majority of the settlement from resaturation is caused by infiltrating water destroying negative pore-water pressures between soil peds and to

some degree by slaking of the soil peds. Water intake continues with time as air is displaced and as water gradually reaches smaller pores. The mean initial and final moisture contents of the samples tested was 19.5% and 27%, respectively. This increase is due only to the intake of water on resaturation. It corresponds to an absolute volumetric swell factor about 15% from the in situ conditions.

5. DISCUSSION OF TEST RESULTS

Figure 13 is a plot of the total strain that occurred over a test sequence versus the final test pressure. The amount of strain tends to maximize at a confining pressure of 150 kPa. This corresponds to an overburden depth of approximately 7.5 m.

Figure 14 is a plot of the strain that occurred during resaturation versus final confining pressure. Generally, the amount of strain during resaturation decreased as the confining pressure increased.

These data cannot be analysed within the context of any widely accepted model such as Terzaghi consolidation or finite strain consolidation. At present, there is no way to evaluate the heterogeneous soil structure by understood mechanisms such as Darcy's Law and stress/strain relationships. The consolidation curves, in general, do not follow the standard E-log p shape, the true effective stress is not known, and the fluid ingress cannot be readily modelled due to the rapidly changing permeabilities that develop because of swelling upon resaturation. Ultimately, an empirical observational approach to relating the data to the field is most likely to be of value. This is, however, not a general rule for all geomechanical systems. It is always useful to explore mechanisms, even if absolute quantification does not ensue. Once mechanisms are identified correctly, improvements can be postulated.

Without measurements of suction, which is difficult under these conditions, the effective stress for the unsaturated sample cannot be determined. Qualitatively, however, resaturation has two effects: First, effective stress due to suction or negative pore water pressure is destroyed, reducing lump strength; second, the smectite can swell or slake in the presence of resaturation water. The material then becomes free to deform plastically, particularly at lump contact points. Macroporosity is largely destroyed, but microporosity is increased upon resaturation. (Microporosity refers to the porosity within the lumps only, macroporosity to the porosity between the lumps).

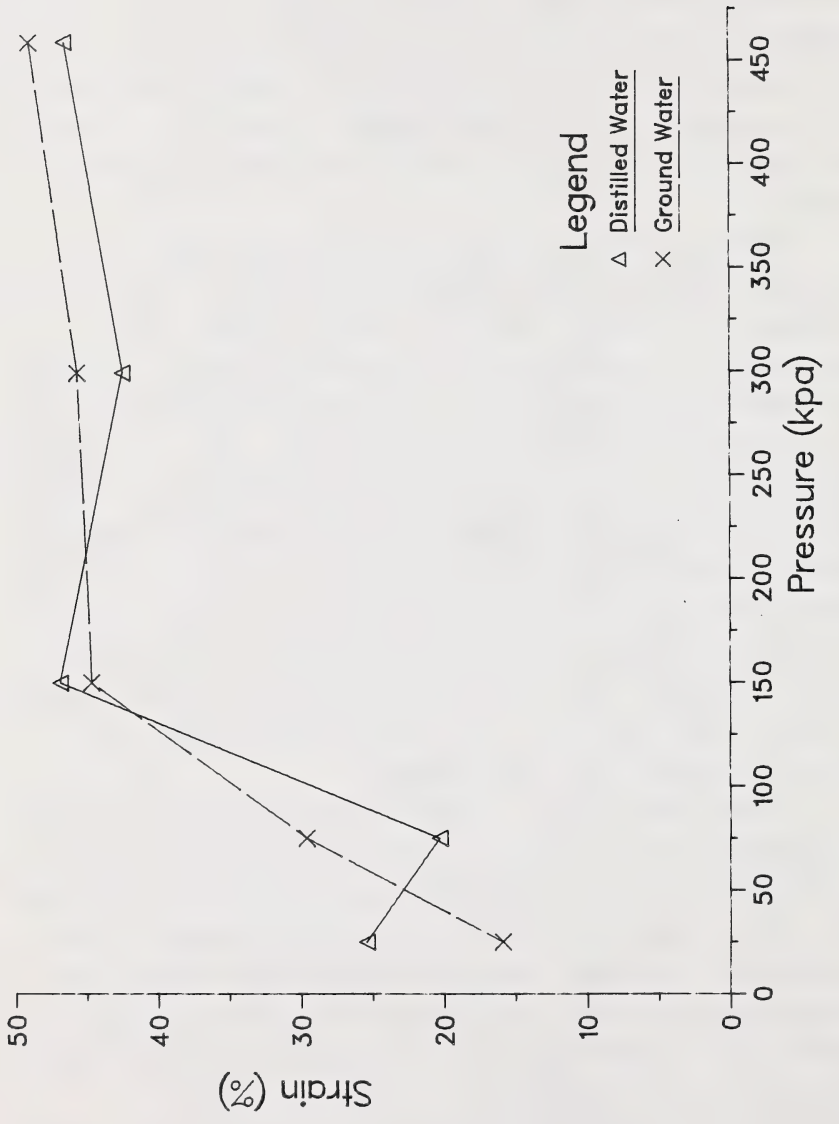

Figure 13. Total strain for compaction and resaturation at various stress levels.

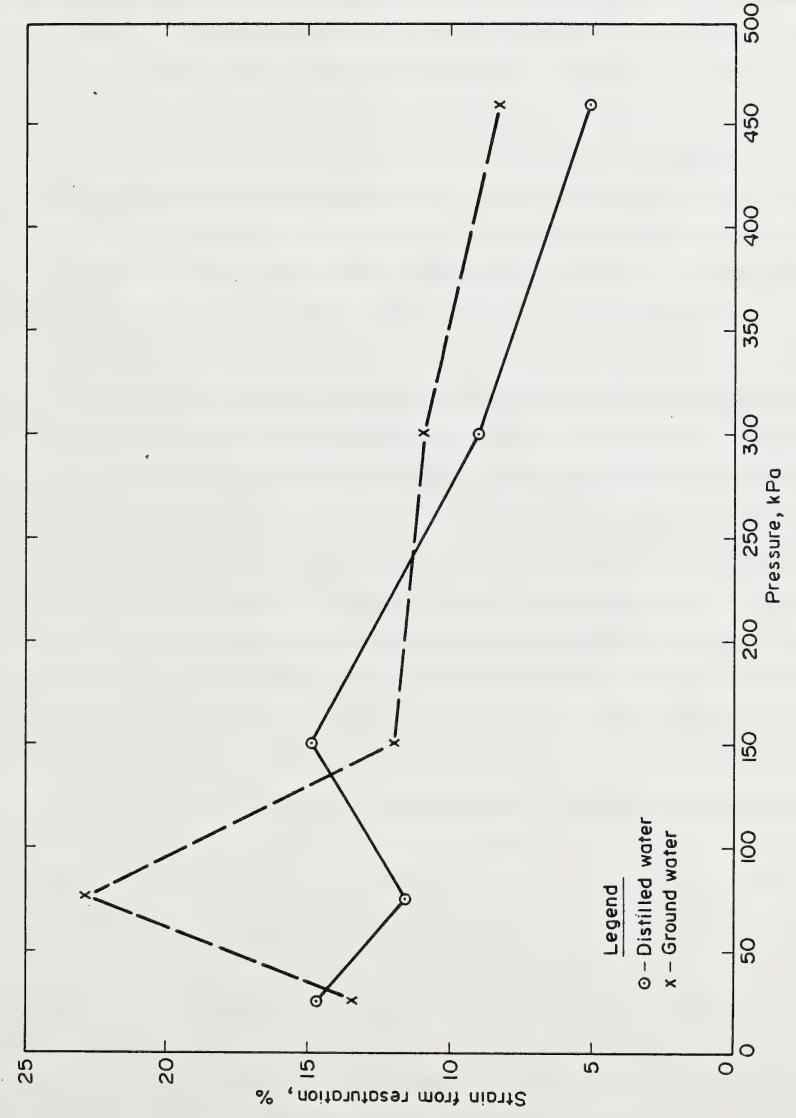

Figure 14. Resaturation strain at various stress levels.

Salinity of the resaturation fluid has been observed to have an appreciable effect on the swell/slake behavior of intact stress-free lumps (Dusseault et al. 1983a). This effect is negligible in a system under stress with a macroporosity network; no difference was observed that can be ascribed to salinity differences. The ultimate magnitude of subsidence in undercompacted zones will, therefore be similar whether resaturation is from percolating meteoric water or from upward movement of somewhat saline groundwater. Large-scale permeability is reduced because of the destruction of the macroporosity by the slake/swell mechanisms and dissipation of pore-water suction.

The vertical strains associated with resaturation occur rapidly, but water intake is delayed. This can be attributed both to the permeability reduction on exposure to water, and to the high suction and capillary rise potential of the gravitationally compacted spoil. That is, some water is rapidly sucked up, destroying lump strength and also reducing suction potential (Dusseault et al. 1983c). However, once lump strength is initially destroyed, the rate of vertical movement slows greatly, despite the sample being undersaturated. Slow continuation of movement (consolidation) can, however, continue for extremely long periods of time due to the low permeability of the partially resaturated smectitic spoil. Gradual dissolution and diffusion of free air is also a slow process, and plays an important role in the permeability changes and consolidation processes during compaction by saturation with water.

6. RELATION TO FIELD BEHAVIOR

Material dynamically compacted on windrows by dragline casting is less susceptible to resaturation subsidence because the macroporosity is on the order of 10%. When water becomes available, it is entirely consumed by the swelling of smectitic material into the voids. At the base of deep spoil piles, stresses may be large enough to allow a few percent strain on rewetting, but nowhere near the strains observed in the valleys or in loose spoil pile heaps.

In the uncompacted regions (valleys), the potential strain upon resaturation can approach the mean value of 10% implied in Figure 14. Local surface deformations of up to 1 m have been observed in valley fills no deeper than 6 to 8 m. An average value of 0.5 to 0.8 m for depths of subsidence bowl corresponds to an average 10% strain.

Zones of active compaction presently developing in the field are observed to be 1 or 2 m above the slowly rising groundwater table. This is confirmation of the lump-softening hypothesis: Capillary rise of water of several metres destroys lump integrity (destroys effective stress) and downward percolation helps contribute to the effects closer to the surface. The two zones in which lump effective stress has been lost through resaturation will ultimately meet when enough water has been made available. This effect in the field can be expected to be greatly delayed due to permeability reduction.

Continuing highway distress is being observed at least eight years after levelling and reclamation. Examination of the vertical strain curves in Figures 8 to 12 shows that, even in a relatively thin sample, deformation continues for a long time. The retardation effect is due to the low permeability of the smectitic material. Incidentally, this can occur only if there is sufficient macroporosity to allow the smectitic clays to swell enough so that consolidation strains can develop. If the spoil is quite dense initially, the equilibrium void ratio may be greater than the sum of the macroscopic and microscopic void ratio, and therefore, the mass

would not tend to enter into the realm of long duration consolidation.

An important question arises at this point: Can laboratory tests actually model true field behavior in systems of this type? It is believed that true modelling cannot be done in the laboratory, even with the relatively large oedometers used. The data do, however, simulate field behavior very well. The difference between the terms modelling and simulation is critical: Modelling implies that a scaling procedure exists that can reliably predict field magnitude from laboratory data; simulation implies that the process be replicated and studied in the laboratory, but that the data cannot be transferred directly in a predictive mode to field behavior. It is claimed that these tests are simulations only because it is not possible to fully include the effects associated with the wide range of lump size seen at the mines; the field material is, in part, dynamically compacted, particularly in the windrows; laboratory tests incorporate one-dimensional straining, whereas the field geometry is strongly bidimensional; and the material in the field has a much greater degree of nonhomogeneity in properties, in moisture access, and in pore fluid salinity.

Consequently, the processes themselves can be studied under controlled laboratory conditions, but the actual field behavior requires a direct observational approach before guidelines can be rationally evolved.

7. CONCLUSIONS

The phenomena associated with the post-reclamation subsidence of smectitic spoil can be simulated in the laboratory under controlled conditions and compared to actual field behavior. Some of the more important conclusions are:

1. The salinity of the resaturation fluid has no effect on the amount or rate of settlement.
2. Resaturation destroys lump effective stress, causing collapse of the microporosity as well as swell/slake deterioration of lumps.
3. Resaturation settlement is rapid once water is available, but water intake is slower than vertical deformation rate.
4. Long-term consolidation continues well after resaturation, but at a significantly reduced rate.

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Report 2: WATER SENSITIVITY OF SMECTITIC OVERBURDEN: PLAINS REGION OF ALBERTA

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ABSTRACT

Subsidence features such as sinkholes and large depressional areas have been observed to develop on reclaimed mine spoil long after releveling and resoiling has been completed. One of the goals of this study was to investigate the mechanisms responsible for differential subsidence by evolving a simple, reliable, repeatable methodology to characterize overburden material with respect to its ultimate behavior upon reclamation. Other goals were to evaluate the water sensitivity of the overburden materials of the Vesta and Paintearth Mines and to relate these results to the lithology, clay mineralogy, and engineering index behavior of the materials.

Overburden core samples from the Diplomat Mine site near Forestburg, Alberta were subjected to Atterberg limit index tests and to pore fluid analysis for identification and classification purposes. Static slaking tests were performed on intact core samples by immersing them in distilled water and observing, at regular intervals, their tendency to slake (breakdown and disaggregate) and swell (increase in the volume of the sample due to imbibition of water by the clay minerals present).

The major conclusions of the study are as follows:

1. The transitional materials of the plains regions are sensitive to water because they are largely free of true mineral cement and they contain significant quantities of swelling clay minerals;
2. Simple tests cannot successfully discriminate among materials of varying sensitivity to water. These tests give a qualitative assessment of the tendency of transitional materials to swell and slake in stress-free aqueous environments;
3. Sufficient discrimination among materials cannot be achieved to categorize lithologies for purposes of selective placement, thereby eliminating many potential problems of the post-reclamation period.

1. INTRODUCTION TO THE SWELLING AND SLAKING STUDY

1.1 STATEMENT OF THE PROBLEM

Observation of reclaimed strip mines shows that subsidence continues well beyond the time of leveling and resoiling. The evidence for this is seen in reclaimed fields where a distinct corrugated surface develops with time (Figure 1). This corrugated surface is evidence of differential settlement within a generally subsiding soil volume. Highways constructed on previously reclaimed areas show significant differential settlement, giving rise to an undulated surface with signs of road-base distress, requiring repeated resurfacing (Figure 2). Some areas within the reclaimed farm land show bowls of depression covering fairly large areas (25 m by 15 m) (Figure 3). These bowls have poor drainage characteristics as they tend to pond water and thereby inhibit high quality utilization. Shallow suface ponds can have considerable amounts of colloidally suspended solids (smectitic in nature) that do not settle with time.

Other problems of decreased productivity resulting from piping, erosion, excessive wetness, and salinity arise long after reclamation. There is reason to believe that the behavior of these spoiled smectitic materials is related to their water sensitivity, to the state of total and effective stress, and to the salinity of the fluids that resaturate the spoil. However, there seems to be no reasonably rapid means of assessing the water sensitivity of the mined smectitic clay shale, and clay-containing sandstone; therefore, there is no quantitative and acceptable method of categorizing the behavior of the materials for reclamation purposes on the basis of the available cored material and geophysical data prior to mining. As these data are collected systematically before mine development and continuous operation, a predictive framework permitting behavioral evaluation beforehand would seem to have value.

Subsidence features have been noted at many other surface mining sites in Great Britain, United States of America, and Alberta.

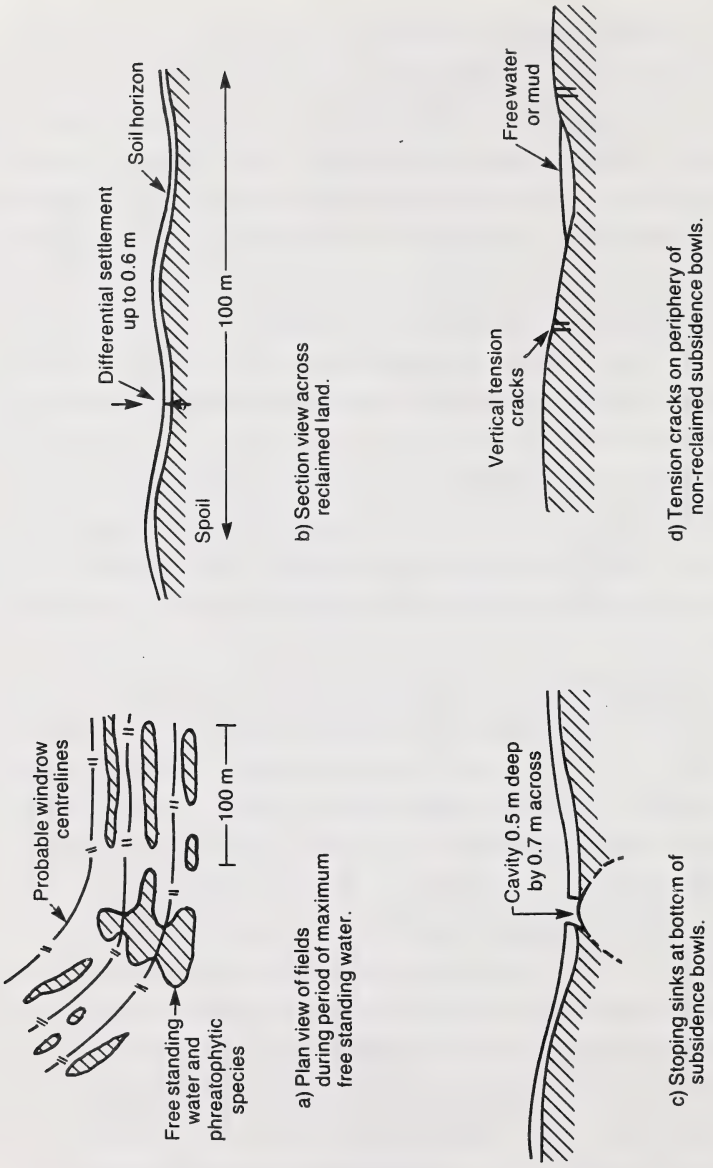
Probable windrow centrelines
Free standing water and phreatophytic species
100 m
a) Plan view of fields during period of maximum free standing water.
Differential settlement up to 0.6 m
Soil horizon
Spoil
100 m
b) Section view across reclaimed land.
Cavity 0.5 m deep by 0.7 m across
c) Stoping sinks at bottom of subsidence bowls.
Vertical tension cracks
Free water or mud
d) Tension cracks on periphery of non-reclaimed subsidence bowls.

Figure 1. Features of subsidence observed on reclaimed land.

Figure 2. Monitoring site on Highway 855.

Figure 3. Reclaimed area of Diplomat Mine site.

The magnitude and time duration of the settlement varies between sites, but most reported subsidence is triggered by changing water conditions in the reclaimed spoil. The purpose of this study is to assess the water sensitivity of the mine spoil from the mine area near Forestburg, Alberta as a qualitative measure of the susceptibility of spoil to settle when it becomes exposed to free water.

The swell/slake test developed by Dusseault et al. (1983) is described and the data from tests performed on the Diplomat overburden are presented. The tests are inexpensive and simple, replacing more involved testing procedures to assess the effect of free water on the engineering properties of these materials.

1.2 GEOMECHANICS OF SPOILING AND POST-RECLAMATION BEHAVIOR

The mine process disaggregates the overburden material, causing it to undergo an increase in volume. The initial porosities of the materials mined ranged from 15 percent for a siltstone with the interstices filled with saturated clay minerals, to perhaps 35 to 40 percent for a smectitic clay shale with little silt or sand, but large percentages of smectite. During mining, the overall volume may increase by 10 to 20 percent. This new volume is in the form of macro-porosity, as opposed to the original material, which has only micro-porosity (Figure 4). Spoil material dumped from the dragline bucket undergoes dynamic compaction, but relatively large voids can still exist between the "lumps" of mined material. The lumps themselves may be fissured by the stresses associated with mining and casting, and these fissures, although very narrow in themselves, represent conduits for water to penetrate rapidly into the soil structure. Lumps that are near the top of spoil heaps are not confined by stress, and are exposed directly to meteoric water and freeze/thaw processes, which further break down the lump size.

In the unmined condition, the material is under some state of effective stress and pore water pressure associated with the presence of a relatively stable water table. Typical stresses after

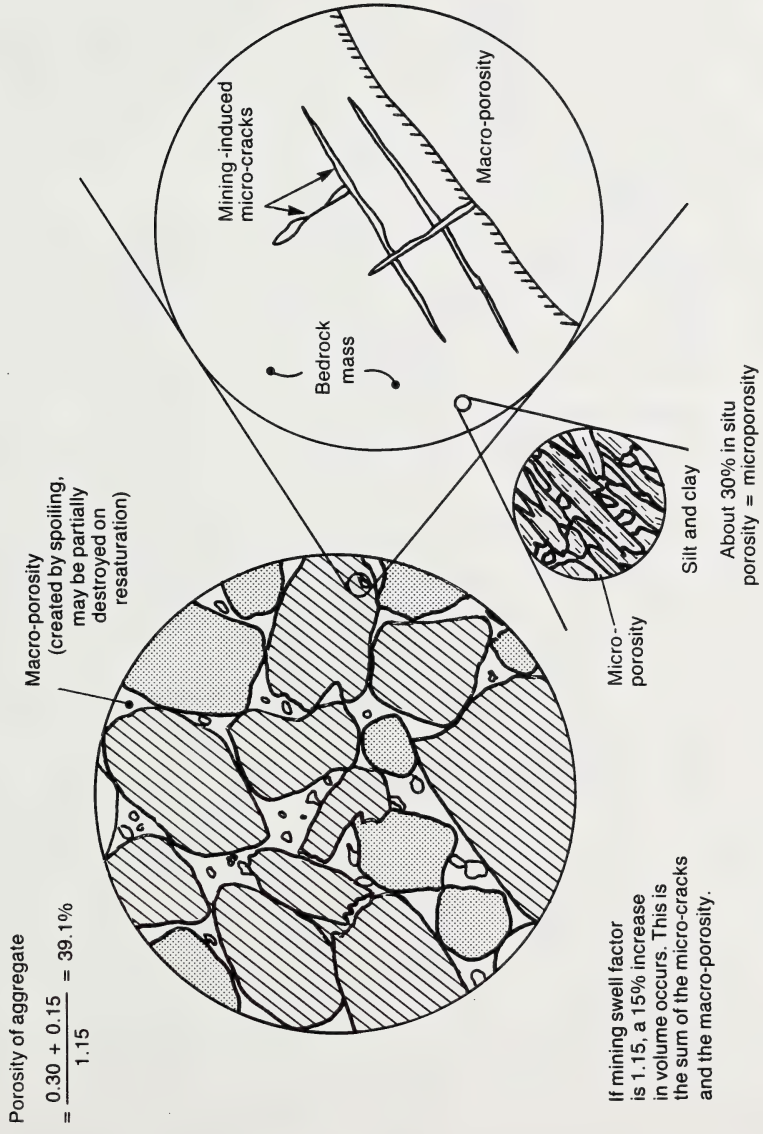
Porosity of aggregate
$= \frac{0.30 + 0.15}{1.15} = 39.1\%$
Macro-porosity
(created by spoiling, may be partially destroyed on resaturation)
If mining swell factor is 1.15, a 15% increase in volume occurs. This is the sum of the micro-cracks and the macro-porosity.
Micro-porosity
Silt and clay
About 30% in situ porosity = microporosity
Bedrock mass
Mining-induced micro-cracks
Macro-porosity

Figure 4. Macro- and micro-porosity of spoil.

mining are shown in Figure 5. Because of the fine-grained nature of most of the overburden, mining causes the pore water to be thrown into a tensile state (suction) that gives the lumps individual coherence; that is, they have a strength arising from the capillary forces associated with the very small pore structure. This stress can be destroyed by resaturating the spoil, or by drying and rewetting to disaggregate the fabric.

Leveling of the windrows results in placement of redisaggregated material into the troughs. Furthermore, the troughs between windrows are sites of water accumulation before leveling and may have experienced extensive swelling and slaking. The material placed between windrows is, therefore, in an under-compacted and highly disturbed state, whereas the sites of the original high windrows are over-compacted with respect to the final reclaimed stress state. The mechanism for differential compaction is identified as arising from the nature of the spoiling/leveling operations themselves. Other factors may influence the ultimate behavior as well; such as, incorporation of masses of snow in spoil heaps, climatic variables such as intensity of winter conditions or summer rainfalls, and the presence of compacted mine structures such as haul roads and ramps.

Once the material has been reclaimed, resaturation takes place and the voids between lumps are filled with either upward rising groundwater as the water table recovers, or with downward percolating water from rainfall or surface ponding (Figure 6). The suction of the individual lumps is destroyed as the lumps imbibe water. They slake and swell, lose their competence, and the ground surface may settle appreciably. At the time this study began, the amount of settlement was not known, nor was it understood whether the settlement was concentrated in the low-stress surface layer, in the high-stress bottom zones where compactive forces are high, or distributed evenly throughout the spoil depth. The materials were known to swell upon stress-free exposure to fresh water, but the effect of this on the behavior of the reclaimed surface was not

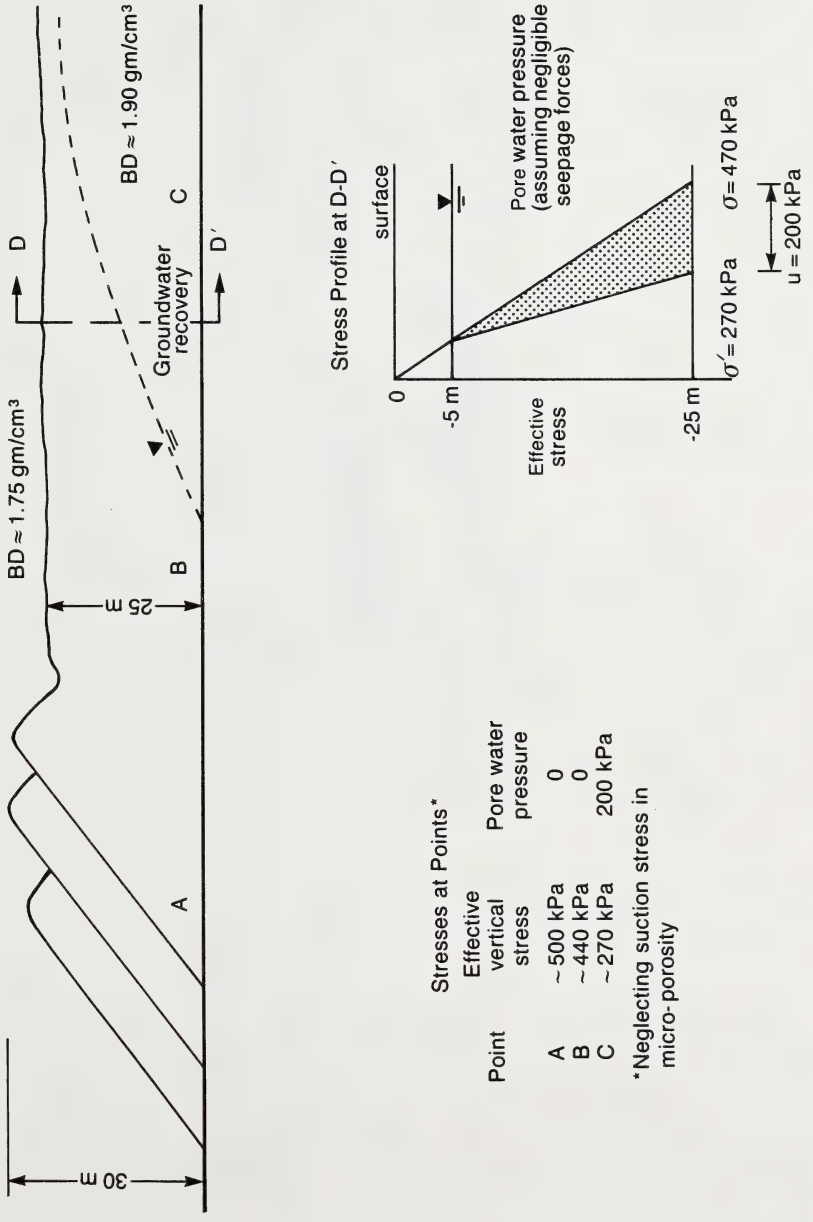

Figure 5. Typical stress during and after reclamation.

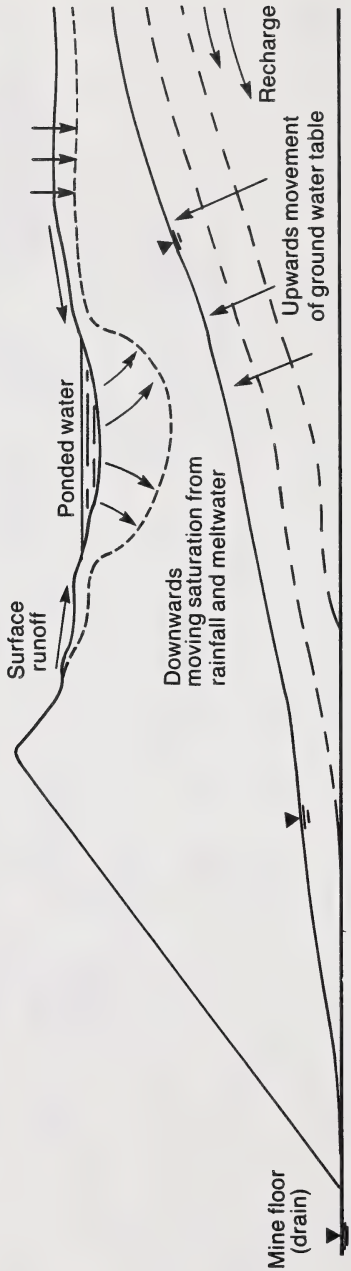

Figure 6. Re-saturation of spoil.

known. The time required for the complex processes to occur had never been quantified in an empirical sense, nor was much information available on the effects of the water sensitivity of the materials on the overall behavior.

These questions had to be addressed for a complete understanding of the subsidence process. This report contains the results of a small part of the geotechnical investigation of the behavior of overburden. It is concerned with swell/slake of the overburden material as sampled by coreholes, and an attempt will be made to relate this behavior to standard index properties and geophysical log data. Other parts of the study are complimentary and ongoing: monitoring of sites for subsidence at surface and at depth; and laboratory tests to measure the behavior of spoiled material on resaturation at different confining stresses.

1.3 STUDY GOALS

The goals of this study were:

1. To evaluate the water sensitivity of the overburden materials of the Vesta and Paintearth Mine areas;
2. To evolve a simple, reliable, repeatable test methodology to characterize the overburden materials before mining with respect to ultimate behavior of the spoil upon reclamation;
3. To try and relate these results to the lithology, clay mineralogy, and engineering index behavior of the materials.

Although the study was performed on materials from the Battle River mining area, the results and conclusions are, to some degree, generalizable. Caution is advised in extension to other sites as variations in mining methods, geological conditions, and conditions of groundwater and climate may yield different behaviors.

2. SAMPLING AND TESTING

2.1 INTRODUCTION

The methods of obtaining, storing, and testing samples are for the most part well understood as standard ASTM practice has been followed wherever applicable. This section is a summary of the methods used. If more detailed descriptions of methods are of interest, reference to other work is recommended (Dusseault and Cimolini 1981; Dusseault et al. 1982).

2.2 SAMPLING PROCEDURES

Cores from the Vesta and Paintearth Mine areas were collected by the PHRP. One hundred and twenty-one samples, each approximately 100 mm in length, were take from seven testholes. As well, one 150-mm sample was selected from each hole to be used in pore fluid extraction for cationic determination.

The samples were placed in plastic bags immediately after removal from the core. The air was evacuated from the bags before they were sealed. The samples were then sealed inside another bag, and stored in a high humidity atmosphere at 16°C until testing.

2.3 SAMPLE PREPARATION

Upon removal from the bag, the samples were carefully scraped to remove any remaining drilling mud. The samples were then divided into two equal parts, each stored in a sealed container. At no time during the experimental program were samples allowed access to water or to drying conditions; sample disturbance was, therefore, limited to that which had occurred during coring and transport. As this degree of sample disturbance is largely unavoidable, it is felt that material of this quality can always be obtained with ease for testing.

2.4 INDEX TESTING

Immediately after the samples were removed from the sealed bags, the moisture content was determined. Approximately 20 g (wet) of material was taken from a freshly exposed specimen face and placed in a preweighed container. The sample was weighed, dried in an oven at 105°C for 24 hr, and reweighed to find moisture loss. To ensure consistent results, the moisture content was determined twice for each sample.

Atterberg limit tests were performed on samples from five cores. Testing procedure followed ASTM standards (ASTM, Part 19 D423, D424). High carbon content shales and coal/shale mixtures were impossible to test for plasticity indices. Tables 1 to 5 list results of the index testing.

2.5 PORE FLUID ANALYSIS

Pore fluid from six samples (the seventh was spoiled) was analysed for cation content. The compressive method of pore fluid extraction was used. This method involves physical squeezing out of a sample the pore liquid for analysis. It is considered to be no less reliable than other methods, and is convenient. The sample was placed in a high pressure cylinder (Figure 7) and subjected to approximately 50 MPa in a compressive frame until 5 mL of fluid was collected in an attached hypodermic vial (usually 36 to 48 hr).

The cation content data are reported in Table 6 and show a reasonably consistent cation content of approximately 2000 ppm with one notable and unexplained exception.

2.6 STATIC SLAKING

The static slaking test consists of placing a cleaned intact core sample (Figure 8), about 50 mm in length, into a 1000 mL beaker containing 400 to 500 mL of distilled water. Care is taken to ensure that the samples are placed into the beakers with as little disturbance as possible of either the sample or water. The samples are observed at intervals of 0, 1, and 10 min and 1, 5, and 24 hr and

Table 1. Engineering index properties, PHRP 5-2.

Depth (m)	Lithology	w (%)	w_l (%)	w_p (%)	I_p (%)	I_l
1.35 to 1.60	Shale	25.9	70	35	35	0.26
2.74 to 3.45	Shale	26.6	48	26	22	0.03
3.45 to 3.64	Siltstone	20.6	43	30	13	0.72
3.64 to 3.89	Sandstone	20.0	73	24	49	0.08
4.88 to 5.13	Mudstone	32.0	84	23	61	0.15
5.50 to 5.60	Shale	24.1	84	22	62	0.03
7.25 to 7.62	Shale	20.6	114	35	79	0.18
7.89 to 8.74	Siltstone	21.9	120	29	91	0.08
12.03 to 12.91	Mudstone	17.9	120	30	90	0.13
15.13 to 15.63	Shale	26.3	78	39	39	0.33
18.52 to 19.02	Shale	21.7	63	32	31	0.33
19.02 to 19.72	Sandstone	13.3	41	22	19	0.46

Table 2. Engineering index properties, PHRP 6-3.

Depth (m)	Lithology	w (%)	w_l (%)	w_p (%)	I_p (%)	I_l
0.00 to 2.44	Clay	25.6	85	36	49	0.21
4.76 to 4.87	Coal-Shale	34.8				
5.78 to 5.89	Mudstone	29.2	113	39	74	0.13
5.89 to 7.14	Shale	25.3	164	35	129	0.08
9.24 to 9.76	Shale	14.1	84	34	50	0.40
10.03 to 10.14	Sandstone	13.2	46	18	28	0.17
10.58 to 11.44	Coal-Shale	33.4				
16.25 to 16.81	Shale	21.3	96	39	57	0.31
17.42 to 17.76	Sandstone	15.8	79	27	52	0.22
18.51 to 19.18	Shale	16.1	117	31	86	0.17
21.95 to 22.48	Coaly-Shale	30.7	105	43	62	0.20
23.80 to 24.40	Siltstone	13.4	58	25	33	0.35
24.40 to 24.38	Sandstone	11.9	59	24	35	0.35

Table 3. Engineering index properties, PHRP 10-2.

Depth (m)	Lithology	w (%)	w_l (%)	w_p (%)	I_p (%)	I_l
0.00 to 0.40	Till	23.1	31	16	15	0.47
3.92 to 4.89	Sandstone	16.2	48	22	26	0.22
9.55 to 9.75	Sandstone	16.0	48	24	24	0.33
10.35 to 10.50	Shale	26.3	67	30	37	0.10
16.14 to 16.71	Shale	30.5	93	30	63	0.01
17.24 to 17.30	Shale	16.5	72	24	48	0.16
18.85 to 19.10	Shale	13.7	72	29	43	0.36

Table 4. Engineering index properties, PHRP 23-3.

Depth (m)	Lithology	w (%)	w_l (%)	w_p (%)	I_p (%)	I_l
0	Till	16.6	30	16	14	0.04
5.93	Till	17.8	32	17	15	0.05
8.39	Sandstone	18.3	49	22	27	0.14
11.95	Clay	20.6	89	36	53	0.29
13.17	Sandstone	17.1	115	33	82	0.19
16.45	Mudstone	19.3	95	41	54	0.40
17.46	Mudstone	26.2	94	40	54	0.26
19.04	Sandstone	14.5	105	39	66	0.37
20.44	Shale	25.0	71	28	43	0.07
23.25	Shale	38.7	65	31	34	0.23
24.84 to 25.21	Sandstone	11.4	80	25	55	0.25
26.01	Sandstone	14.0	79	25	54	0.20

Table 5. Engineering index properties, PHRP 24-2.

Depth (m)	Lithology	w (%)	w_l (%)	w_p (%)	I_p (%)	I_l
0	Till	14.7	30	16	14	0.09
7.01	Shale	18.9	97	35	62	0.26
7.56	Sandstone	21.0	116	30	86	0.10
7.97	Siltstone	28.6	201	32	169	0.02
9.08	Siltstone	24.5	184	32	152	0.05
12.66	Shale	20.3	132	35	97	0.15
13.72	Shale	29.3	97	33	64	0.06
14.34	Sandstone	27.4	60	24	36	0.09
14.59	Shale	19.0	81	34	47	0.32
15.85	Siltstone	11.3	133	30	103	0.18
17.65	Shale	14.6	121	38	83	0.28
19.51	Sandstone	15.6	142	26	116	0.09
22.18	Shale	12.4	85	28	57	0.27
23.98	Coal-Shale	24.3				
26.03	Siltstone	27.6	118	41	77	0.17
28.60	Shale	19.1	105	32	73	0.18
29.86	Coal-Shale	30.6				
30.02	Sandstone	11.7	83	26	57	0.25

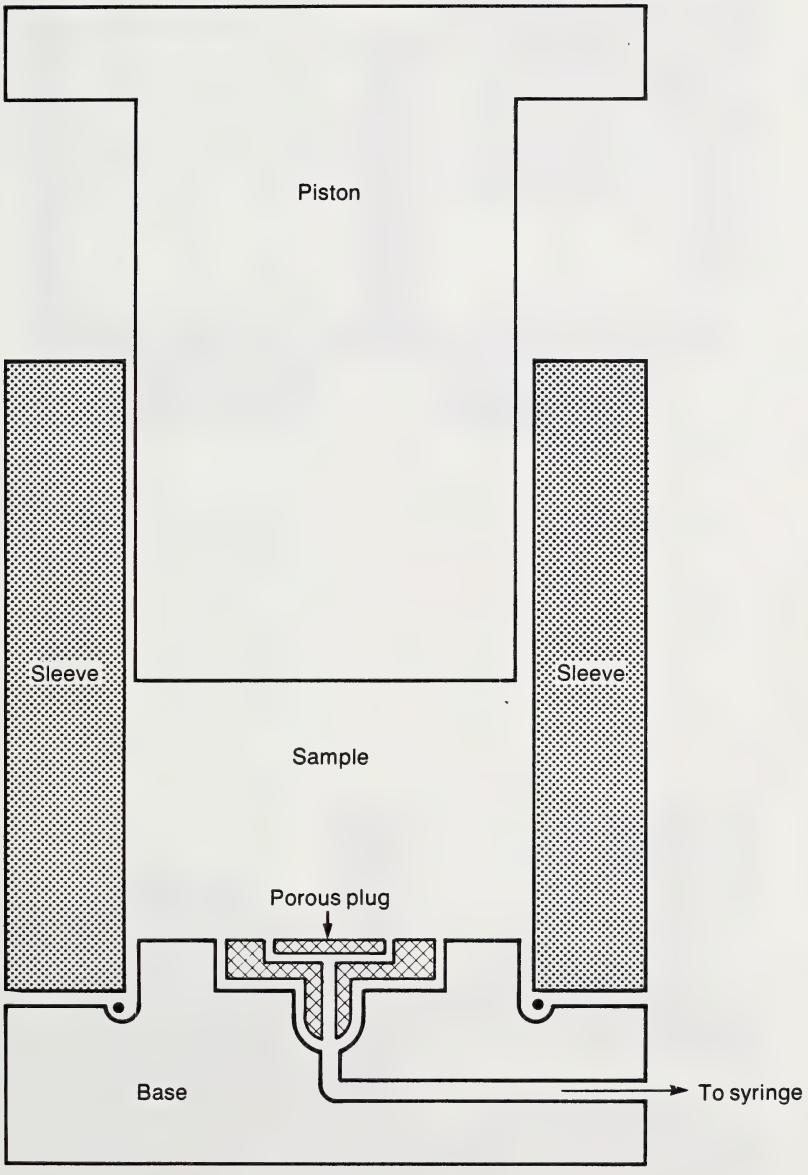

Figure 7. Pore fluid extraction device.

Table 6. Cation concentrations for selected lithologies.

Sample Number	Lithology	Natural MC[1]	Plasticity Index	Cation Concentration (ppm)					
				Fe	Ca	Mg	K	Na	Total
10-3	Sandstone	16.1	24	trace	417	132	30	1413	1992
23-10	Shale	38.7	35	trace	31	11	12	1564	1618
29-2	Siltstone	23.5		trace	155	81	81	1324	1614
5-11	Shale	21.7	31	trace	58	5	19	2030	2112
24-7	Shale	29.3	65	trace	119	23	35	1874	2051
6-6	Sandstone	13.2	27	trace	trace	7	17	350	376

[1]MC: moisture content.

Figure 8. Two overburden core samples prior to immersion in slake/swell container.

Figure 9. Samples in Figure 8 after 24 hours in distilled water.

classified according to the system outlined in Table 7. Figure 9 illustrates two samples after 24 hr. At 24 hr, the cohesiveness of the sample was determined by probing the sample with a thin steel rod. The scale used in the classification is a descriptive one, yielding qualitative data only. The stringent laboratory requirements for a quantitative swell/slake test precludes the development of a rapid economic test applicable to large numbers of specimens and suitable for lithological classification purposes. Reference to published data confirms this (Holmgren and Flanagan 1977; Lew and Schmidt 1977; Moriwaki and Mitchell 1977). Other tests are too lengthy (Eigenbrod 1972) or too destructive for the nature of the materials tested (e.g., Franklin and Chandra 1972).

All samples were tested at their natural moisture contents. The decision to test only field moist material was based on the assessment that any desiccation would give rise to behavior not relevant to the goals of the study. Desiccated samples, usually found near to the ground surface, were not tested as the slaking of these samples is considered misleading. Table 8 contains the results for hole PHRP 24-2.

Table 7. Classification for the slake/swell test.

Category	Classification and Slaking Determinations Description
A	No sample deterioration.
B	Slight deterioration (water clear, minor flecks or fragments).
C_1	Medium deterioration. Original shale largely reserved.
C_2	Surface deteriorated. 1. Water murky 2. Water clear
D_1	High amount of deterioration. Original shape large or
D_2	completely destroyed. Many flecks or fragments. 1. Water quite murky 2. Water slightly murky
E_1	Total disintegration.
E_2	1. Water completely muddy 2. Water slightly muddy
E_3	3. Water clear

Swelling Categories	
No swelling	No increase in volume
Little swelling	Slight increase in volume
Medium swelling	20 to 50% increase in volume
High swelling	50 to 100% increase in volume
Very high swelling	>>100% increase in volume

Table 8. Slaking behavior, PHRP 24-2.

Depth (m)	Immediate Behavior	1 Minute	10 Minutes	1 Hour	5 Hours	24 Hours
0	Moderate Slaking	C_2	C_1	D1	E2	E3
7.01	Slight Slaking	B	B	C_1	C1	D2
7.56	No Reaction	B	C_1	C1	C1	D2
7.97	No Reaction	B	B	C_1	C1	D1
9.08	Slight Slaking	B	C_1	C1	C1	D2
12.66	No Reaction	A	B	C_1	D_2	D2
13.72	Slight Slaking	A	C_1	D_2	D2	D2
14.34	Slight Slaking	B	C_1	C1	C1	D2
14.59	No Reaction	A	A	B	C_1	C1
15.85	No Reaction	A	C_2	C1	C1	C1
17.65	No Reaction	B	B	C_2	D2	E2
19.51	No Reaction	A	C_2	C2	C2	C2
22.18	Slight Slaking	A	B	B	B	B
23.98	No Reaction	A	A	A	B	B
26.03	Moderate Slaking	B	C_1	C1	D1	D2
28.60	Slight Slaking	B	C_1	D2	D2	D2
29.86	No Reaction	A	B	B	B	B
30.02	No Reaction	A	C_2	C2	C2	C2

3. DISCUSSION

3.1 GEOLOGIC MATERIALS OF THE ALBERTA PLAINS REGION

The bedrock overburden overlying coal beds in the plains of Alberta, which was deposited during the Cretaceous and Tertiary periods, has properties that make it neither soil nor rock and thus it has been termed 'Transitional Material'. The overburden is not soil because it is greatly over-compacted and has varying degrees of cementation; it is not rock because lithification has not progressed to the point of making it strong and rigid. A classification system for these materials is suggested in the report entitled 'Classification System for Transitional Materials: Plains Region of Alberta' by Dusseault et al. (see p. 87 of this volume).

As much as 10 m of glacial deposits cover the transitional materials. In some mine areas where the till layer is quite thick and the overall thickness of overburden is thin, such as the Diplomat Mine, the till material makes up a predominant portion of the spoil.

3.2 SUBSIDENCE MECHANISMS

The strip mining process dissaggregates the overburden materials to varying degrees producing a spoil with an assortment of lump sizes and some fine material. When the overburden is broken up by the mining process, small micro-cracks form in the lumps as they expand from unloading (Figure 2). This increase in volume at a constant water content causes the material to become unsaturated. The unsaturated spoil lumps retain their competency and strength as suction pressures from capillary forces develop in the unsaturated voids and micro-cracks. When these lumps are exposed to free water they imbibe water through both matrix and osmotic suction causing loss of strength.

When water from surface infiltration and a rising groundwater table becomes available to the spoil, matrix suction, caused by the negative pore pressure, draws water into the spoil lumps. As the lumps imbibe water, the pore pressure rises from a

negative suction value to a positive hydrostatic value. The stress between soil grains is greatly reduced so that the spoil weakens and flows to fill the macro-voids in the spoil.

Osmotic suction occurs where fresh water in the macropores comes into contact with the spoil that commonly contains more saline solutions in the macropores. Water is drawn into the spoil lumps by osmosis of the fresh water and the saline solutions. An inherent charge deficiency of the clay minerals also attracts the polar water molecules. Together these mechanisms of water absorption cause slaking and even swelling of stress-free spoil. The tendency of the spoil to swell depends on its clay mineralogy, the salinity of the available water, and the overburden pressure.

An indirect measure of the quantity and type of clay mineral is the liquid limit. All the bedrock overburden materials tested in this study have high to very high liquid limits indicating consistently large proportions of smectitic clay minerals (Figure 10). The term smectitic refers to the family of swelling clay minerals. The family contains several mineral species including the more commonly known montmorillonite species. The till materials of the same area have much lower liquid limits. They too contain large clay portions, but of a different species than the bedrock. Direct determination of clay mineralogy indicates that 87 percent of the clay minerals in the bedrock are smectite, whereas only 43 percent of the clay minerals in the till are smectite (Maslowski Schutze in press). The mining process does not alter the plasticity of the materials as is shown in Figure 10 where spoiled bedrock is of similar plasticity to the premined bedrock and the plasticity of the spoiled till is identical to the premined till.

Mine spoil contains lumps of overburden containing various quantities of smectitic clay minerals and with various suction potentials. As water becomes available to the spoil, subsidence will be slow and ongoing as lumps slake at various rates. Also, the permeability of spoil varies, depending on the macro-porosity of the spoil and is reduced as the spoil slakes and swells. Subsidence may

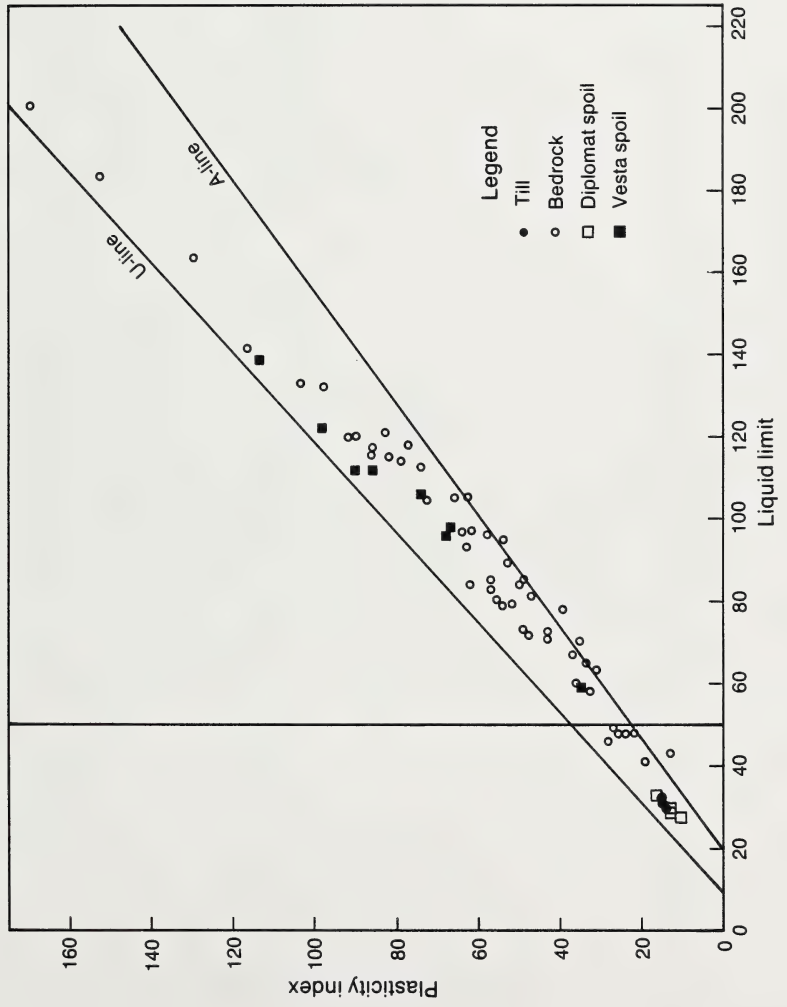

Figure 10. Plasticity of overburden soils and rocks.

continue even after groundwater table recovery as isolated zones of spoil become sealed off from groundwater flow.

3.3 SLAKING OF SPOIL SAMPLES

The complete set of swell/slake tests performed on the samples from hole PHRP 24-2 is shown in Figures 11 to 15. The curves present three-point moving averages providing a visual assessment of the mean behavior of the materials. This hole show the rapid deterioration demonstrated by many transitional materials. The slaking of the spoil samples was compared with other properties of the material. Figure 16 shows the degree of slaking at 24 hr plotted against the described lithology for premined sample material from seven boreholes. It was hoped that the swell/slake test would reveal those strata that are most sensitive to water, thus identifying potentially undesirable materials. However, little discrimination between materials is revealed by the tests. Sandstone, siltstone, mudstone, shale, and till all undergo a range of slaking behavior.

The degree of slaking at 24 hr of material from five boreholes shows no relationship to the liquid limit of the sample material (Figure 17). Materials containing large proportions of smectitic clay particles, as shown by the high liquid limits, can range in slaking activity from C2 to E3 categories, similar to materials of medium to low plasticity. Soil mechanics theory suggests that the slaking of materials is dependent on their grain size composition (lithology) and on their clay particle portion and type (plasticity); however, this is not supported by our data. Further, investigation of the Vesta Mine materials indicate that two other properties, carbon content and cementation, also play a prominent role in the slaking activity of the materials.

Carbonaceous material is common in sediment in coal-bearing sequences. Carbon content of the overburden materials ranges from almost no carbon to coal. Clayey coal and carbonaceous shale samples showed considerably less slaking. These materials are not

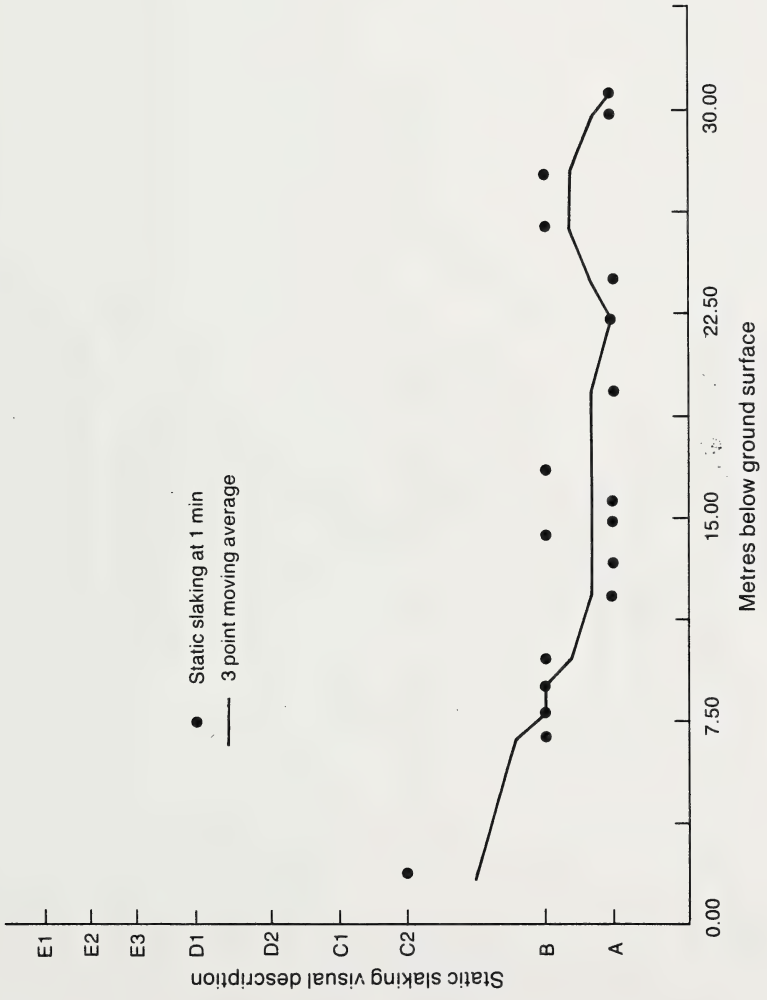

Figure 11. Static slaking at 1 minute, PHRP 24-2.

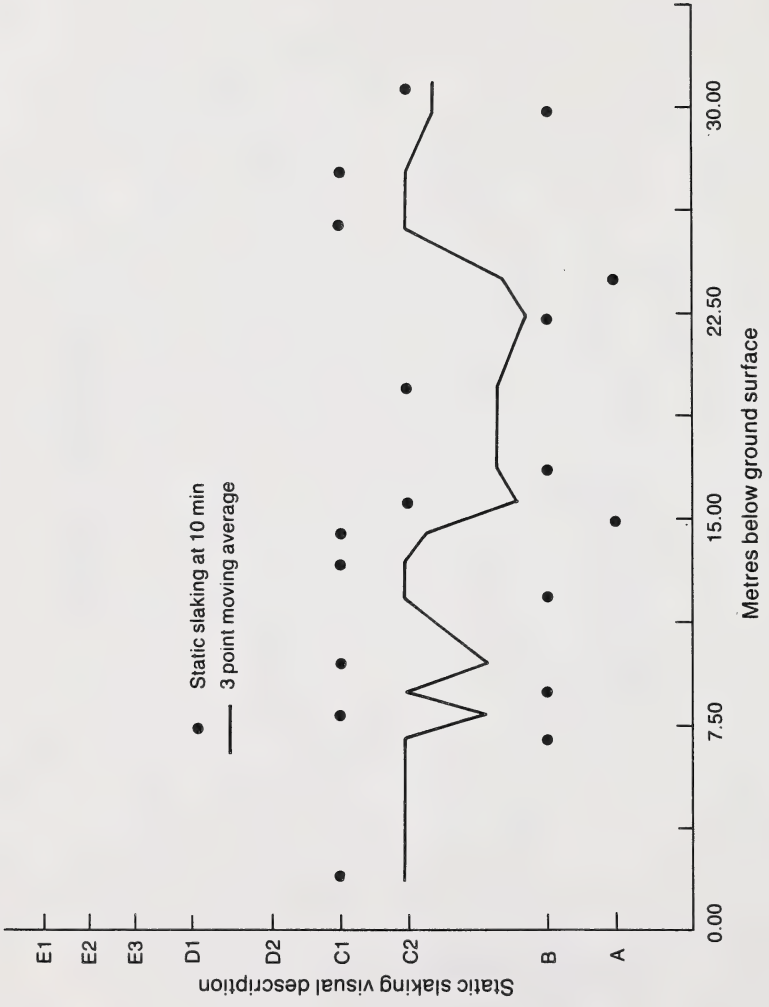

Figure 12. Static slaking at 10 minutes, PHRP 24-2.

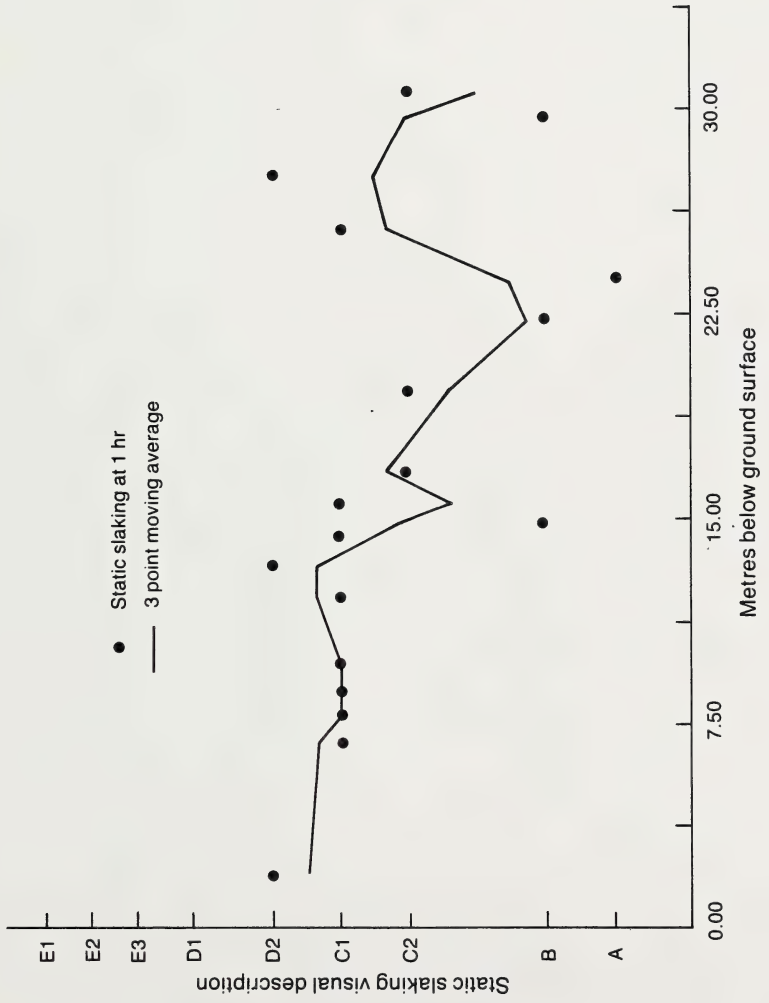

Figure 13. Static slaking at 1 hour, PHRP 24-2.

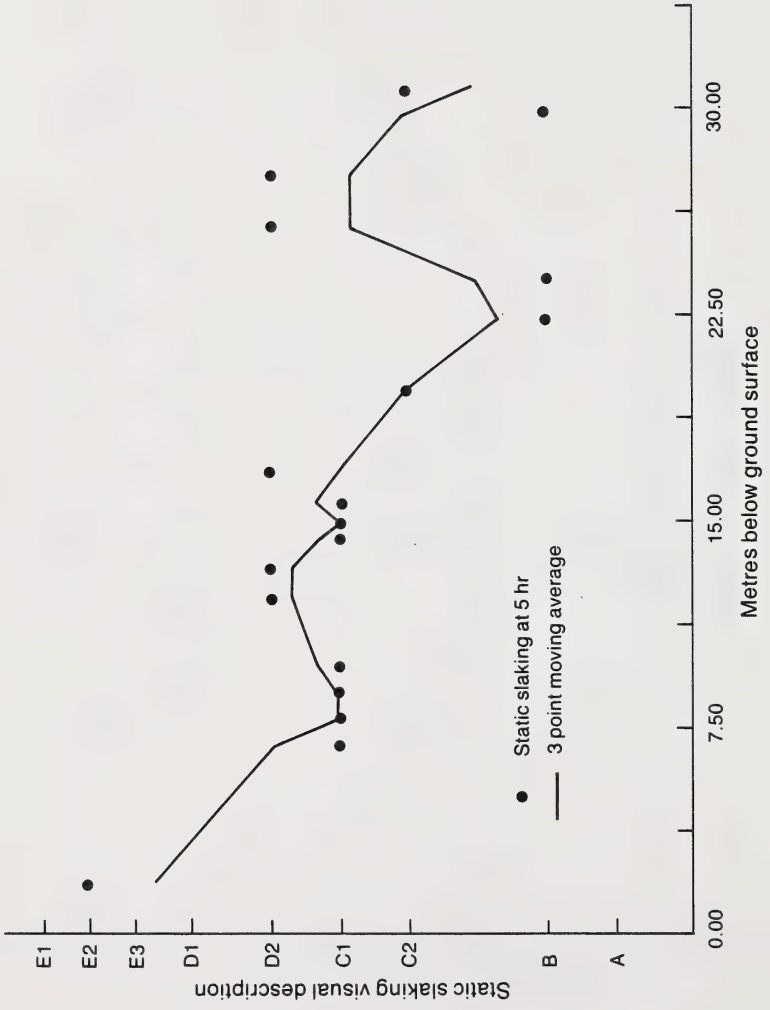

Figure 14. Static slaking at 5 hours, PHRP 24-2.

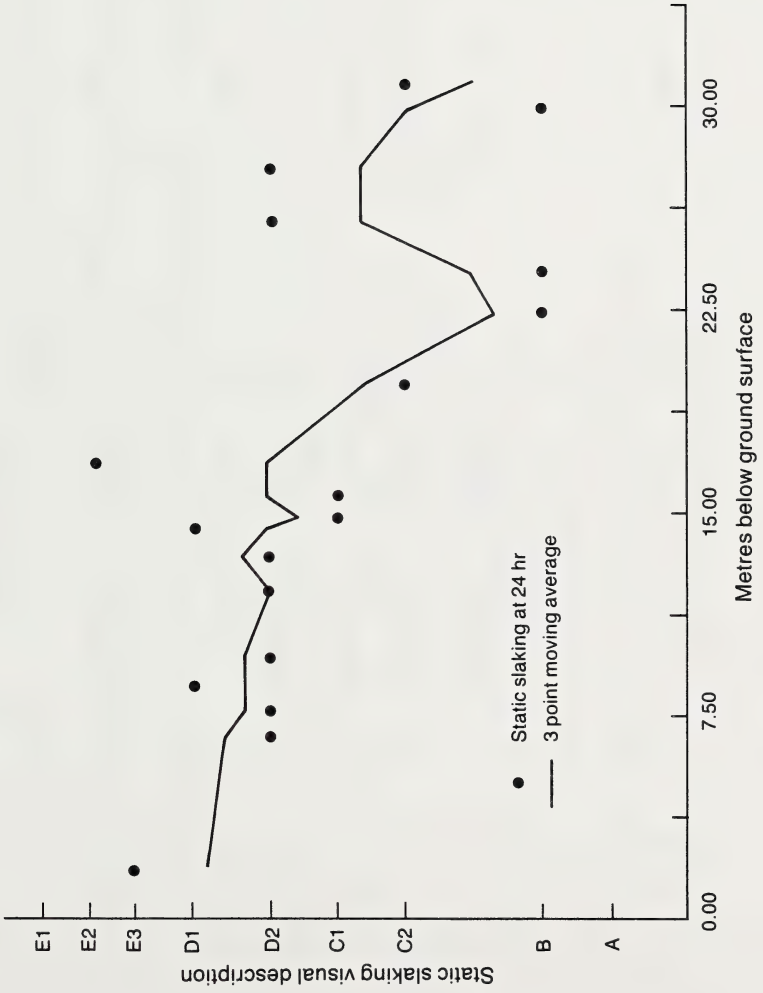

Figure 15. Static slaking at 24 hours, PHRP 24-2.

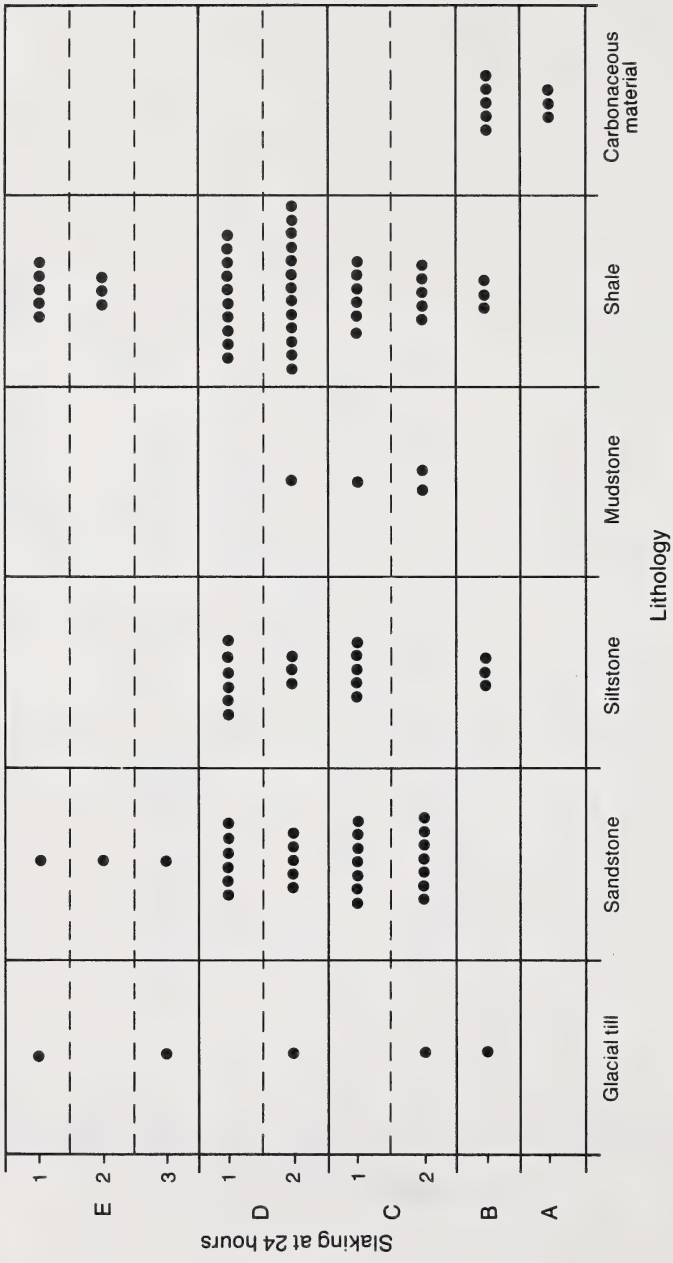

Figure 16. Static slaking versus lithology.

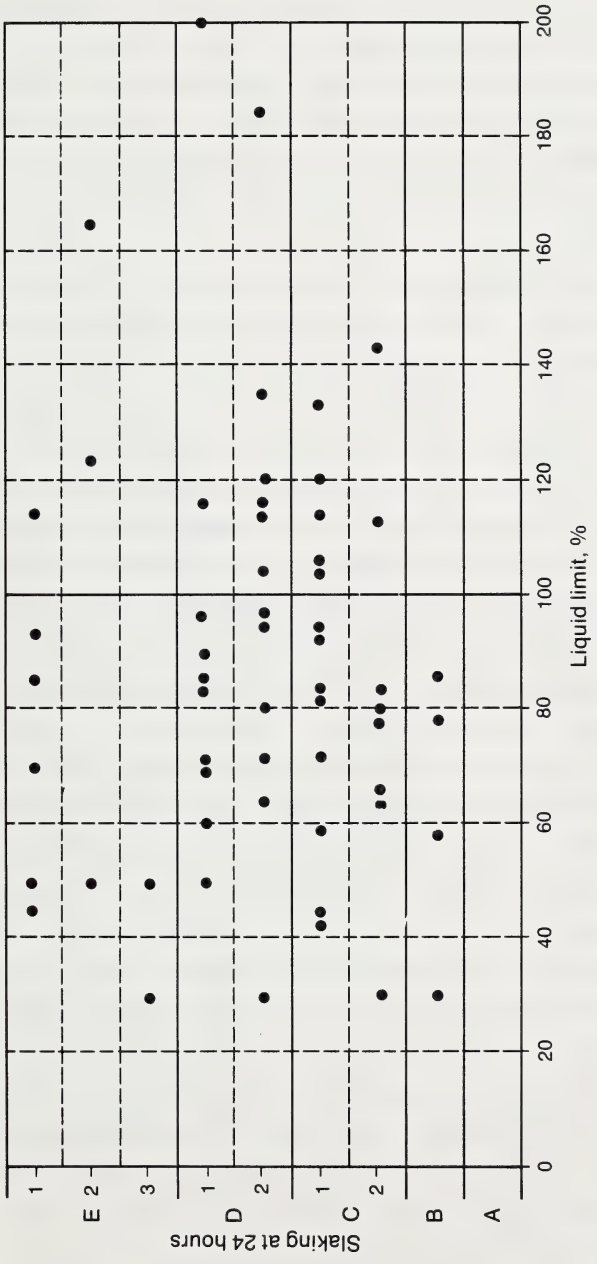

Figure 17. Static slaking versus liquid limit.

susceptible to large settlement on rewetting, but do not make up a significant portion of the spoil.

Cementation also reduces slaking behavior. The amount of cementation was not measured, but on the basis of the ranges of slaking behavior shown by various lithologies, it seems that cementation is not concentrated in any one lithology. Sandstone, siltstone, and shale all have a great range of slaking tendency suggesting varying degrees of cementation in all lithologies.

No useful correlations between the swell/slake test and index properties are apparent. Soil mechanics suggest that materials with high clay content have high liquid limits and, therefore, should undergo severe slaking and swelling. The swell/slake test would be used to readily indentify these undesirable materials. However, the varying degrees of carbon content and cementation of the materials obscures any correlations suggested by soil mechanics. As there is a great range of carbon content and cementation in all lithologies, the slaking and swelling characteristics are unpredictable and will not discriminate undesirable transitional bedrock materials of the Battle River Mine area.

The glacial till material also exhibits varying degrees of slaking. No cementation is expected in this material as it is normally consolidated. Carbon contents are not expected to vary appreciably as the till material is generally well mixed through the glaciation process. The slaking of till material is governed by the matrix suction of the dissaggregated material since large quantities of smectitic minerals are not present. Osmotic and charge deficiency suction forces will not be appreciable, therefore, the till material will only imbibe water through matrix suction until it becomes saturated. At saturation, a small difference in clay portion of the material then dictates whether the sample will swell slightly, retain its cohesion and appear unaffected by water, or slake to varying degrees.

The swell/slake test does not indicate a dissimilarity between till and bedrock materials. An immediate loss of strength of

the till is observed in the consolidation cell when it is exposed to water, whereas the bedrock transitional material shows a much slower time dependent strain and strength loss from rewetting. The swell/slake test does not indicate this difference in behavior. A correlation between slaking and subsidence potential cannot be made as the slaking test does not visually assess the loss of strength of the sample. The key role of the destruction of matrix suction in the till material, making it susceptible to large settlements, is better investigated through consolidation testing. Osmotic and charge deficiency suction forces of smectitic bedrock materials cause them to slake similarly to glacial tills with high matrix suction. The slaking test will not visually assess the different slaking mechanisms of the bedrock and till of the Vesta Mine area.

The transitional materials will slake completely or swell significantly with no overburden pressure, but the same mechanisms that cause the material to dissaggregate or swell can retard loss of strength under load conditions where only a limited amount of water can be drawn into the clay structure. The highly smectitic materials remain strong with a limited water content increase. Subsidence in these materials will be concentrated in macro-void zones where the spoil can slake and swell on the stress-free surfaces of spoil lumps. If the spoil is homogeneous, however, a small increase in water content saturating the spoil volume will not reduce the soil strength enough to cause a volume change.

The glacial till material greatly reduces in strength with a slight increase in water content. Significant subsidence is expected even where no macro-voids exist in the spoil. The slaking behavior in a stress-free environment does not indicate this difference in strength loss of the glacial till and the smectitic bedrock.

4. CONCLUSIONS

The following conclusions are formulated from this investigation into the swelling and slaking behavior of materials in the Vesta Mine area:

1. The great majority of bedrock and till overburden materials in the Vesta Mine area slake to some degree due to the matrix, osmotic and charge deficiency suction of water. The low permeability of the spoil and the various rates of slaking of spoil cause slow and ongoing subsidence as overburden lumps loose strength at varying rates.
2. There is no apparent correlation between slaking activity and liquid limit or lithology of overburden materials. Cementation and large amounts of carbon in the smectitic materials inhibit slaking.
3. The swell/slake test cannot be used to discriminate undesirable lithologies as most lithologies indicate a great variance in slaking behavior.
4. The slaking test does not measure loss of lump strength on wetting as is noted in the consolidation testing cell and, therefore, will not identify the undesirable materials that lose strength immediately on wetting.
5. A laboratory consolidation testing program is recommended to investigate the loss of strength of smectitic transitional bedrock materials under the simulated in situ stress condition of the consolidation cell.

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Report 3:

CLASSIFICATION SYSTEM FOR TRANSITIONAL MATERIALS: PLAINS REGION OF ALBERTA

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ABSTRACT

To better deal with subsidence problems associated with releveled mine spoil, the Plains Hydrology and Reclamation Project (PHRP) has developed a lithological classification system that addresses the smectite rich transitional overburden found in the Plains region of Alberta. Also discussed in this report is the use of geophysical logs for engineering and geological purposes.

The major conclusions and recommendations of this study are as follows:

1. A major study integrating clay mineralogy, engineering behavior, lithological descriptions, laboratory methods, and the use of geophysical logs should be initiated. The data from the Forestburg project will serve as the base for this study, however, at least one other site should be studied in similar detail to provide a comparative data base.
2. An investigatory group to standardize laboratory methods for Plains transitional materials should be started. This group should contain engineers as well as soil scientists and geologists. It should be prepared to make recommendations to the Geological Survey of Canada, the Canadian Geotechnical Society, and other groups with interest. Perhaps the committee should be constituted under the auspices of these groups.
3. There are now sufficient data to warrant standardizing the methods of lithologic identification and classification. Ambiguous terms should be dropped or carefully defined and some new terms are worthy of inclusion providing the implications are well understood. A published handbook is strongly recommended.

4. The use of geophysical logs in geomechanics and geology of transitional materials is sufficiently advanced that a handbook of methods and applications should be prepared for exploratory and industrial geologists and engineers working in transitional strata.

Although the PHRP is primarily concerned with applying the results of this study to understand long term differential subsidence of releveled mine spoil, the results of this study are of interest to all engineers, geologists, and soil scientists working with the overburden materials found in the Plains region of Alberta.

1. INTRODUCTION

This report represents the findings of a study done by the Plains Hydrology and Reclamation Project (PHRP) to develop a classification system for transitional materials in the Plains region of Alberta for geological and engineering purposes.

Transitional materials are those geological materials which are neither soil nor rock. They are not soil because they are greatly over compacted and may be significantly cemented in place. They are not rock because natural lithification (rock forming process) has not progressed to the point where they are strong and rigid. Consequently, transitional materials can be expected to weather much more readily than rocks, yet, in an intact state, display significant strengths and high densities. With the exception of infrequently encountered concretionary bands and carbonate-cemented sandstones, all of the Cretaceous and Tertiary strata of Alberta are transitional materials.

The authors propose an expanded lithological classification scheme. Most methods in use at present do not lend themselves to the unusual and important properties of the transitional materials of the prairie bedrock, because few engineering measures are included in a lithological scheme, and because it is very difficult to perform an accurate determination of properties from a hand-specimen or visual core examination. It is felt that the proposed scheme will serve to extend existing methods, render data of more engineering use, will be discriminatory among different materials, and will prove to be inexpensive and rapid.

Another aspect of this study is to investigate the feasibility of using geophysical and lithological logs of overburden for geological and engineering purposes. Although the authors are primarily interested in using the logs as tools to aid in developing the most effective methods for releveling and reclaiming coal strip mine oveburden, the implications of this study are of concern to any group dealing with overburden materials in the Plains region of Alberta.

To investigate the mechanisms responsible for differential subsidence of releveled coal mine spoil, an extensive series of sampling and testing programs to premining overburden cores was performed to evaluate the geology and the engineering properties of the future spoil. Information taken from geophysical and lithological logs of overburden before mining may be used to reduce the number of tests necessary to identify and classify the overburden and mine spoil materials.

1.1 SCOPE OF REPORT

An investigation of geophysical and lithological logs was undertaken as part of a larger study of undisturbed Plains area coal mine overburden. The study was divided into two parts: first, core samples of the overburden were obtained for index testing as well as for a series of tests designed to determine water sensitivity of the overburden. Although some of the results of this part of the study are referred to in this report, the results are fully presented and discussed in "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta" (see p. 41 of this volume). The second part of the study and the subject of this report is a discussion of a classification system for smectitic transitional material.

The proposed classification system is illustrated by the examination of core samples of undisturbed coal mine overburden which were taken from the Vesta Mine site. The Vesta Mine site is located near the Battle River Generating Station approximately 20 km southwest of Forestburg, Alberta. After the boreholes for the core samples were completed, seismic crews logged each borehole with the following logs: caliper, long space density, spontaneous potential, resistivity, gamma ray, neutron-neutron, focused electric, and coal lithology log. The core samples and the corresponding geophysical and lithological logs from seven boreholes were furnished by the Alberta Research Council to the Forestburg Reclamation Study, Investigation of the Settlement Behavior of Mine Backfill.

1.2 AREAS OF POTENTIAL SIGNIFICANCE

The areas where this study may have significance are:

1. Lithological classification of Plains region overburden materials for purposes of engineering as well as geology.
2. Maximizing the use of geophysical logs on overburden material in its premining state and correspondingly reducing coring and testing costs.
3. Mine planning for selective placement of overburden materials of varying properties.
4. Forecasting post-reclamation material behavior.

2. GEOLOGY AND MATERIAL CHARACTERISTICS

2.1 INTRODUCTION

Geological data allow the development of a predictive framework whereby generalizations may be applied through a model to a site, permitting predictions of engineering behavior and extensions of limited data bases. For spoil reclamation, it is necessary to establish the differences in behavior of the different lithologies encountered to determine whether selective handling is worthwhile, and to determine whether corrective measures are warranted or likely to be successful.

2.2 GEOLOGY

The major geological event in western Canada since the Early Tertiary age has been the continental glaciation of the Pleistocene age. The effects on the overburden of the coal seams were two fold: first, glacial erosive forces removed further quantities of material and created zones of bedding plane slip induced by shear stress; second, a veneer of glacial sediments was deposited on the Cretaceous and Tertiary strata.

The sediments associated with glaciation are tills, disturbed bedrock, and glacio-lacustrine sediments deposited in glacially impounded lakes and streams. For the most part, these glacial materials are desirable deposits for construction and reclamation purposes, as they are granular in nature and do not have as much smectite in the clay fraction or as much total dissolved solids in the groundwater as the bedrock material and groundwater.

The glacial activity affected the geotechnical properties of the overburden: first, freeze-thaw phenomena have broken down the highly over-compacted nature of some of the relatively undisturbed strata, resulting in zones of higher porosity with a nuggety texture; second, high shear stresses, combined with elevated pore pressures in the low permeability clay shales, have resulted in the creation of slip planes which usually coincide with the weakest stratum.

It is reasonable to assume that from 800 to 1500 m of sediment have been removed by Tertiary and glacial erosion. The materials are therefore highly overconsolidated with respect to their present loading condition. This overconsolidation, in the geotechnical usage, does not imply cementation, most strata are not cemented and have undergone only mild diagenesis. This has important implications with respect to behavior; the mined volume is considerably greater than the bank volume and the materials are sensitive to water, which enters readily and causes the fabric to expand. The depositional environments associated with coal deposition result in poor lateral predictability of rock units because the strata lense according to the control exercised by the paleo-estuarine conditions. Washouts arising from removal of coal by streams are common, changing roof rock conditions are commonly observed, massive sandstone lenses may disappear within a few tens of metres laterally, and bentonite or clay-rich sediments may be locally absent as the meandering accreting stream courses shifted laterally and excavated new channels.

The implications on overburden behavior prediction are clear, it is expected that the succession of beds must be developed on a lithostratigraphic basis for individual sites, with reliability parameters extracted from geophysical and core data. The predictive model must be based on the frequency of the various lithological units and their average behaviors as well as a depositional environments model.

2.2.1 Lithology

The major lithologies found in the Plains overburden are clay shales (clays), clayey sands and sandstones, siltstones and clayey silts, carbonaceous clay shales, coal in thin seams, till, and glacio-lacustrine silts and clayey silts. In addition, bentonite seams are common, and tuffaceous beds may also be found. Numerous intermediate species exist, and are placed into one or the other category according to the visual assessment of the geologist. A

predictive capacity based on identifiable lithologic subdivisions may lead to generalizations on the engineering behavior of the overburden materials in Plains coal mining. Important variables are: average grain size, percentage of clay minerals, ratio of smectite to total clay mineral content, and carbon content. Work on classifica-tion schemes has gone on for some time (Underwood 1967; Lambe and Whitman 1969; Deen 1981) and as yet there seems to be no widely acceptable schema for those materials referred to as 'transitional'; that is, with properties intermediate to those of soils and rocks.

2.3 GEOPHYSICAL LOGS

2.3.1 Introduction

One of the goals of the Forestburg Reclamation Study, Investigation of the Settlement Behavior of Mine Backfill is to gain a greater understanding of the mechanisms responsible for differential settlement of releveled coal mine spoil. Some of the parameters responsible for the mechanisms include density, porosity, permeability, and clay mineralogy. It is felt that geophysical logs of the mine overburden may, by evaluating the above parameters that affect settlement mechanisms of spoil, be used to predict engineering behavior of the spoil.

2.3.2 Data Base

A typical juxtaposed set of log traces, along with a visual description based on core examination, is presented in Figure 1. The geophysical logs for that borehole have been reproduced directly from the field logs without any adjustments or corrections.

Geophysical logs have three major uses: correlation of strata, lithological interpretations, and predictors of engineering behavior. The first of these three uses is the best established; the third remains somewhat contentious. The major logs of value for correlation, lithology, and engineering behavior are the Spontaneous Potential, Natural Gamma Ray, and Gamma Ray Density logs.

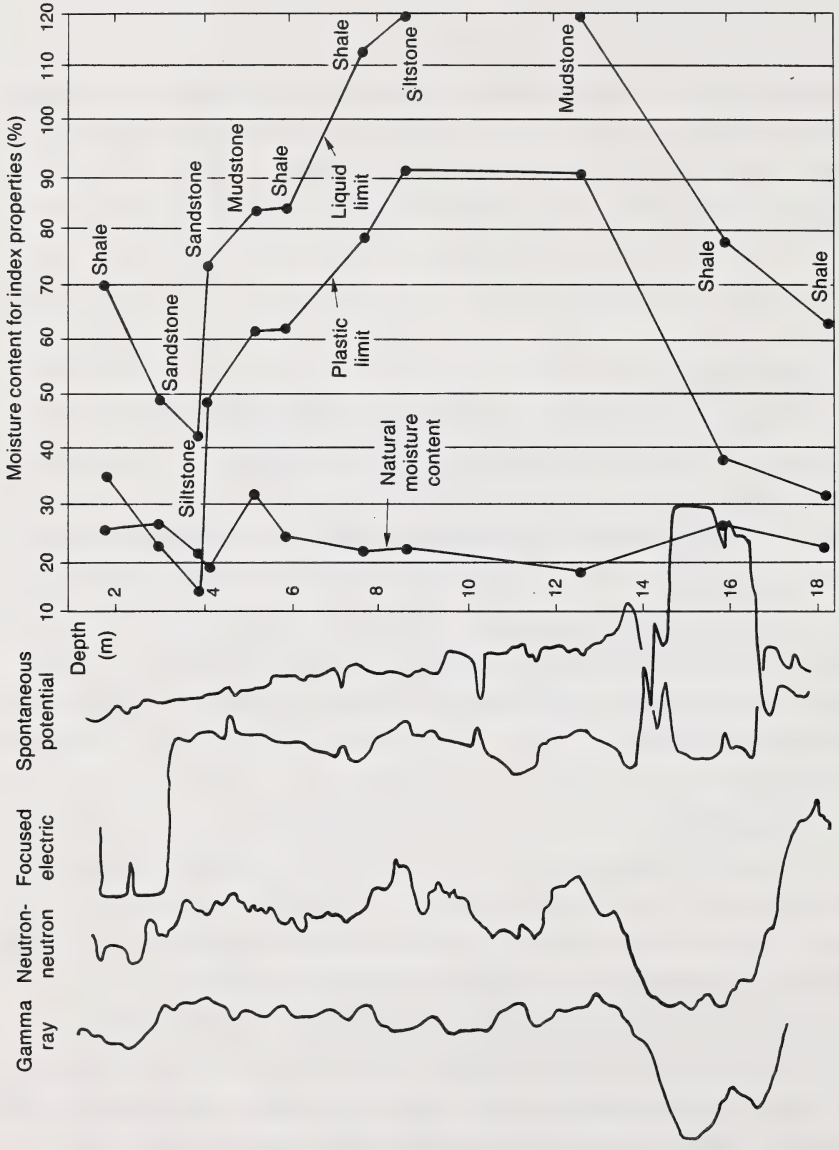

Figure 1. Geophysical logs and engineering index properties for the hole PHRP 5-2.

2.3.3 Correlations Between Holes

In appropriate depositional regimes, the number of coreholes for detailed geotechnical analysis can be reduced by correlation using geophysical logs. This option is available wherever the spacing of the holes necessary to delineate the resource is much less than the distance over which lithofacies changes take place. Use is made of marker horizons, defined by the user, which are observed to give consistent and reliable responses. If the deposit is characterized by lateral continuity, linear interpolation between holes is performed, and volumes and weights of specific beds are calculated directly. If lateral continuity is not a dominant depositional characteristic of the deposit, some more suitable means of interpretation of the borehole data must be used. If there is a defineable interdependence of thicknesses of particular strata between boreholes, a two- or three-dimensional kreiging statistical technique or spline-function methods may be used based on experience and applicability.

For selection of a specific sharp contact between beds, the Spontaneous Potential log often gives highly accurate data. However, in regions where the differences in fluid salinity are not predictable and greatly affected by fresh meteoric water and facies change, the SP log is not a powerful inter-well correlation tool.

Coal seams and concretionary beds may serve as markers due to differences in density from the surrounding strata. Concretionary beds that are regionally continuous are useful for correlations and to correct the relationship between geophysical depth and core depth. Care must be exercised in using potentially lenticular beds as markers. For concretionary beds, the density difference is usually at least 0.3 g/cm^3 (that is, the difference between 2.3 and 2.6 g/cm^3), which provides excellent discrimination. The density difference of coal seams on standard logs is even greater, 0.5 to 0.8 g/cm^3.

Many coal seams have lateral continuity much greater than the drilling density, and give a characteristic signature on various

logs. An example of a good characteristic signature is visible in the geophysical logs for the PHRP boreholes 26-5 and 29-2 (Figures 2 and 3). The sequence of three lower coal beds, two upper beds, and a coaly central bed is repeated faithfully in both holes. However, the character of the individual beds has altered somewhat. Only the major seam, number two from the top, retains a signature that is sufficiently similar for use as a single-bed correlator. These general comments serve to illustrate the use of logs in coal application. It is necessary to have an appropriate and detailed facies model with which to interpret and evaluate material for both resource management and ultimate reclamation.

2.3.4 Lithological Use of Geophysical Logs

The primary indicator of lithology is the natural radioactivity, or gamma ray log. This device measures the emission of gamma radiation by logging with a scintillometer or geiger counter. The basic interpretative assumption is that as the clay content rises, the natural radioactivity also rises. This assumption, while tenable in the gross sense, is in serious doubt in certain geological environments such as that of the smectitic sands and clay shales of the Plains (Isaac et al. 1982).

The major element responsible for the emission of radiation is K^{40}. If only clay minerals contained this element, and if the ratios of clay mineral species remain constant, then the use of the gamma ray log would be straightforward. In typical Plains bedrock, the sandstones are sublitharenitic to arkosic. However, quartzose sandstones are known to occur in all of the Cretaceous strata as well. The more arkosic a sandstone is, the greater the content of potash feldspar and lithic fragments containing clay minerals. In successions of highly quartzose sandstone and clay shales, lithologic discrimination is rapid and precise. In sequences of clayey silts, dirty sands, and silty clays, where the sands are lithic and arkosic, discriminatory ability is reduced. The selection of consistent radioactivity limits to give precision of lithological subdivision is difficult.

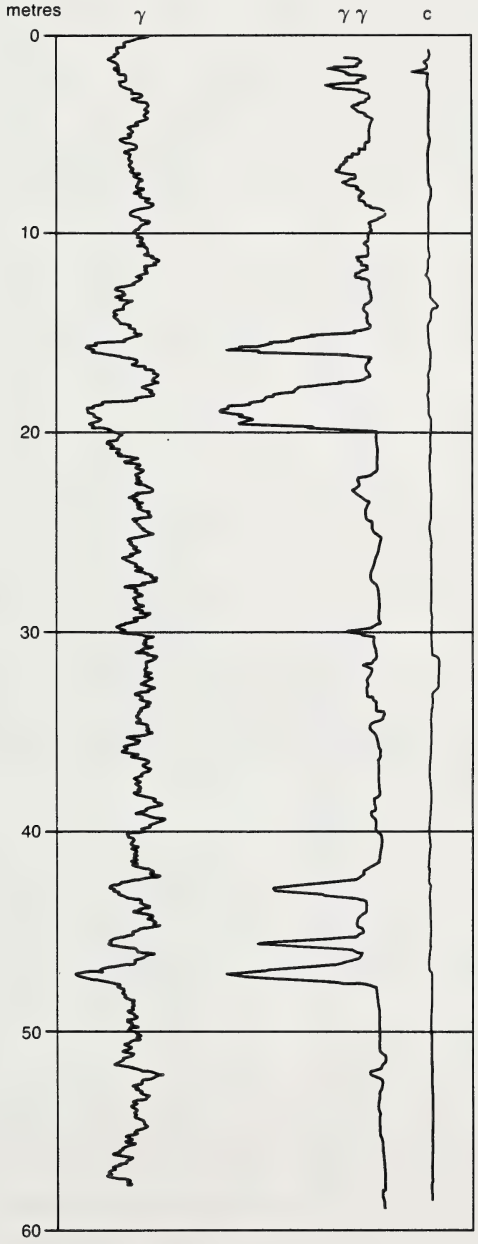

Figure 2. Geophysical log from PHRP 26-5.

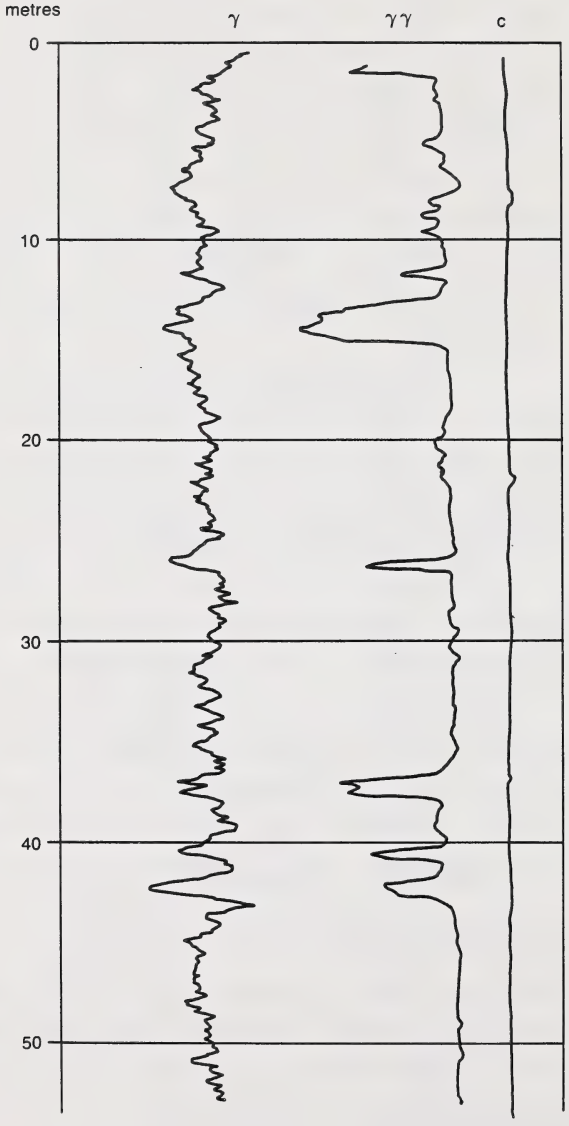

Figure 3. Geophysical log from PHRP 29-2.

Another major assumption used in lithological interpretation is that the ratios of the clay minerals is approximately constant. This assumption is necessary because the various clay minerals have different contents of potassium. Potassium does not substitute readily for either silicon or aluminum in the tetrahedral and octahedral layers and it is found as an interplate cation. Illite has the highest potassium content. Kaolinite does not have an interplate exchangeable cation, therefore little to no potassium is found in the kaolinitic clay minerals. Smectite may have small quantities of potassium, but the cationic species are predominantly sodium and calcium. Other clay minerals are totally absent or present only in small quantities in Plains overburdens and have no effect on the presence of potassium. In many of the clay shales found in overburdens, illite is a major specie. However, in highly smectitic clay shales, the relative concentration of potassium may be so low as to give a natural radioactivity response typical of a silt or dirty sand.

Careful core examination combined with classification tests are necessary before the gamma ray log can be used systematically for lithological interpretation. The radioactivity is not a unique function of any variable, but is a lumped parameter combining radiation components from several sources which cannot be independently separated. An attempt to represent the major factors of the radioactivity response is found in Figure 4, indicating that ambiguous discrimination is possible in the highly variable lithologies found in the study area.

In the case of consistent lithological density differences, Gamma Ray Density log may be valuable. The density log can discriminate effectively in strata containing coal, carbonaceous shales, and concretionary zones. The density log cannot discriminate in silty-sandy-clayey sequences because no unique relationship exists between density and grain size.

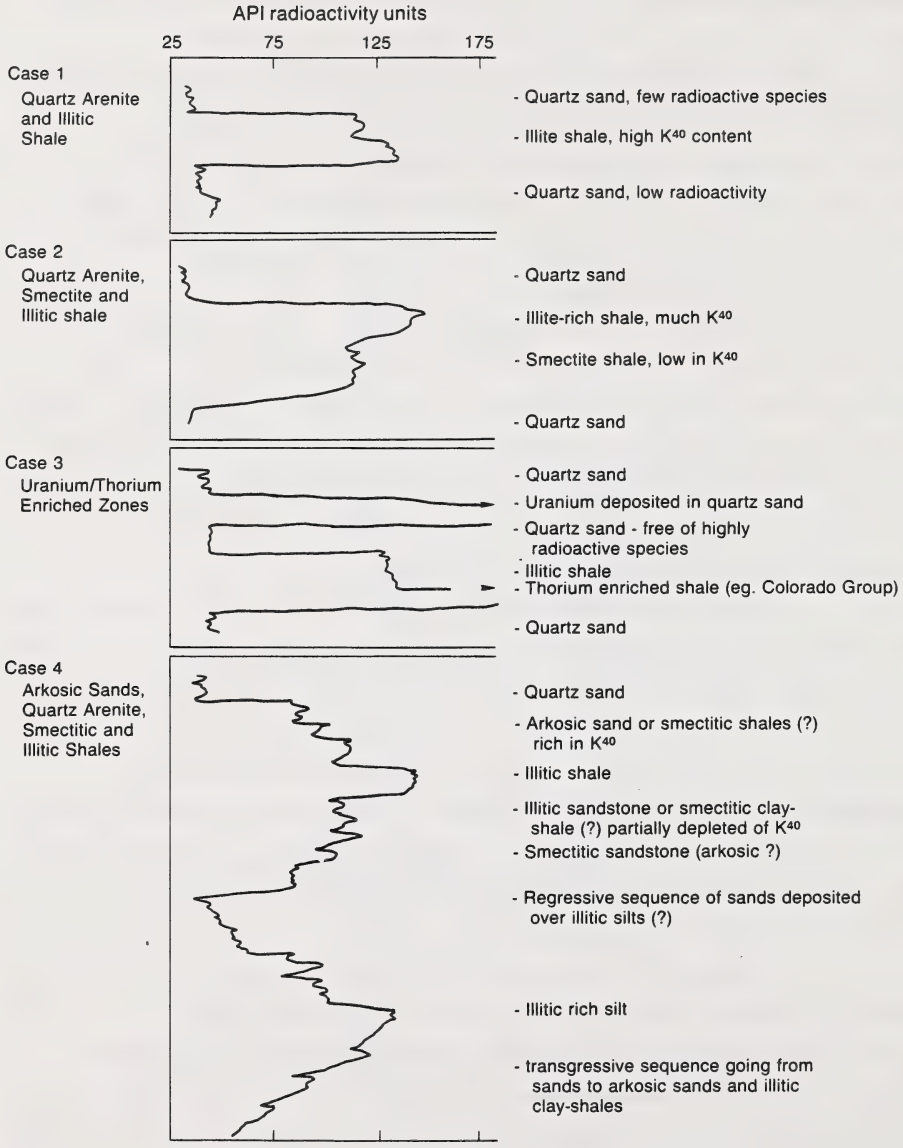
API radioactivity units
25
75
125
175
Case 1
Quartz Arenite and Illitic Shale
- Quartz sand, few radioactive species
- Illite shale, high K40 content
- Quartz sand, low radioactivity
Case 2
Quartz Arenite, Smectite and Illitic shale
- Quartz sand
- Illite-rich shale, much K40
- Smectite shale, low in K40
- Quartz sand
Case 3
Uranium/Thorium Enriched Zones
- Quartz sand
- Uranium deposited in quartz sand
- Quartz sand - free of highly radioactive species
- Illitic shale
- Thorium enriched shale (eg. Colorado Group)
- Quartz sand
Case 4
Arkosic Sands, Quartz Arenite, Smectitic and Illitic Shales
- Quartz sand
- Arkosic sand or smectitic shales (?) rich in K40
- Illitic shale
- Illitic sandstone or smectitic clay-shale (?) partially depleted of K40
- Smectitic sandstone (arkosic ?)
- Regressive sequence of sands deposited over illitic silts (?)
- Illitic rich silt
- transgressive sequence going from sands to arkosic sands and illitic clay-shales

Figure 4. Major features of radioactive response in Plains strata.

2.3.5 Geotechnical Properties from Geophysical Logs

Correlating the physical properties of materials to geophysical log data can greatly reduce the costs associated with laboratory testing and improve the applicability and extent of the data. Correlations that may exist must be sufficiently precise that confidence in their use can be achieved.

The in situ porosity can be obtained directly in the laboratory by volume and mass measurements and by determination of the relative density (D_R) of the minerals. Most of the materials that are encountered in the overburden of prairie mines are sufficiently fine grained that they can be assumed to be saturated. The only exceptions are very permeable sands or glacial materials near the surface above the groundwater table. With the assumption that saturated conditions exist, calculation of porosity or void ratio is simple. Only the water content and the relative density of the mineral matter need be determined. Often, however, coring physically disturbs the samples and the swelling nature of the clay minerals makes reliance on the moisture content impossible. Core treatment after drilling may also lead to desiccation, giving incorrect porosity determinations. If moisture content is known to be reliable, the following equation is used to calculate porosity:

$$\eta = 1 - \frac{\rho_t}{D_R\ (1+\delta)}$$

The authors are of the opinion that the laboratory water content of uncemented smectitic clay shales can never be entirely relied on, and propose that geophysical bulk density logs be used to calculate porosities. The value of bulk density is determined for the appropriate stratum from an accurate gamma ray bulk density log and the relative density is determined by the appropriate laboratory procedure. Great care must be taken to assure direct correspondence between core and geophysical log depths. An assumption of 100% saturation is made and the porosity is then calculated from the following equation:

$$\eta = D_R - \frac{p_t/p\delta}{D_R - 1}$$

The method is sound because great reliance may be placed on the value of bulk density from the Gamma Ray Density log (Dusseault and Van Domselaar 1982). Porosity logs or other geophysical measures of density derived from sonic logs should not be used as their interpretation is not precise or direct in these materials. Figure 5 gives curves relating water content and porosity for several materials, assuming that a clayey sand has a mean relative density of 2.67, a silt has a value of 2.70, and a clay shale has a value of 2.75. These are reasonable assumptions for materials with no carbon present. The higher value for clay shales reflects the usually higher illite content. Figure 6 gives the relationships between porosity and bulk density for saturated materials of differing relative density. Many of the difficulties of geophysical log interpretation can be minimized by careful analysis, correlation, and correction based on a large sequence of logs. This is valuable, but the expense may not be justifiable for a geotechnically oriented investigation program. The additional reliability is often not worth the extra effort, particularly since those properties of greatest interest to geomechanics (for example, shear strength) cannot be obtained directly from logs; they can only be treated in a correlation fashion based on laboratory tests.

The application of geophysical logs to other geotechnical uses is limited for a number of reasons: different clay minerals vary in their ability to retain water; different degrees of sorting and angularity give rise to a range of packings and behaviors; cementitious materials which influence physical behavior are very difficult to identify from geophysical data; and many important geotechnical parameters such as residual shear strength and Atterberg limits cannot be simply related to basic terms from other parameters that geophysical logs might be sensitive to. One purpose of this study is to further explore the possibility that some measure of water sensitivity can be developed from geophysical logs.

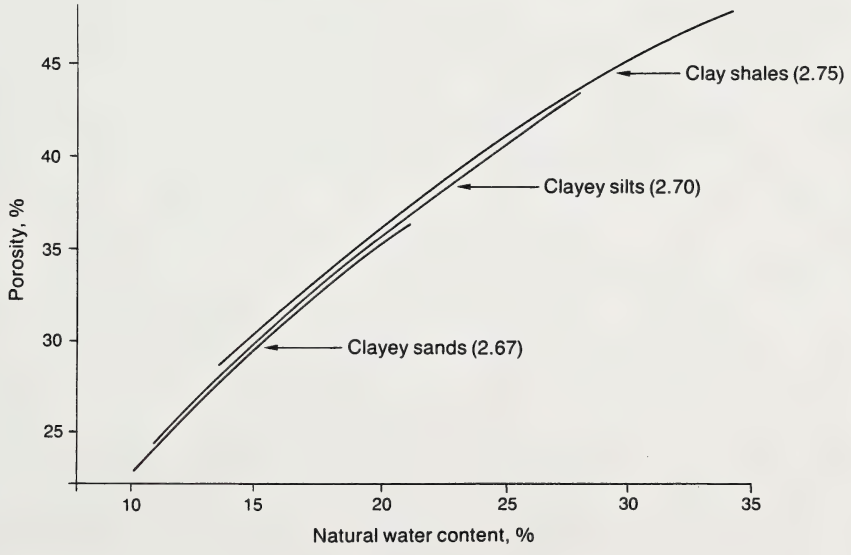

Figure 5. Determination of porosity from natural water content.

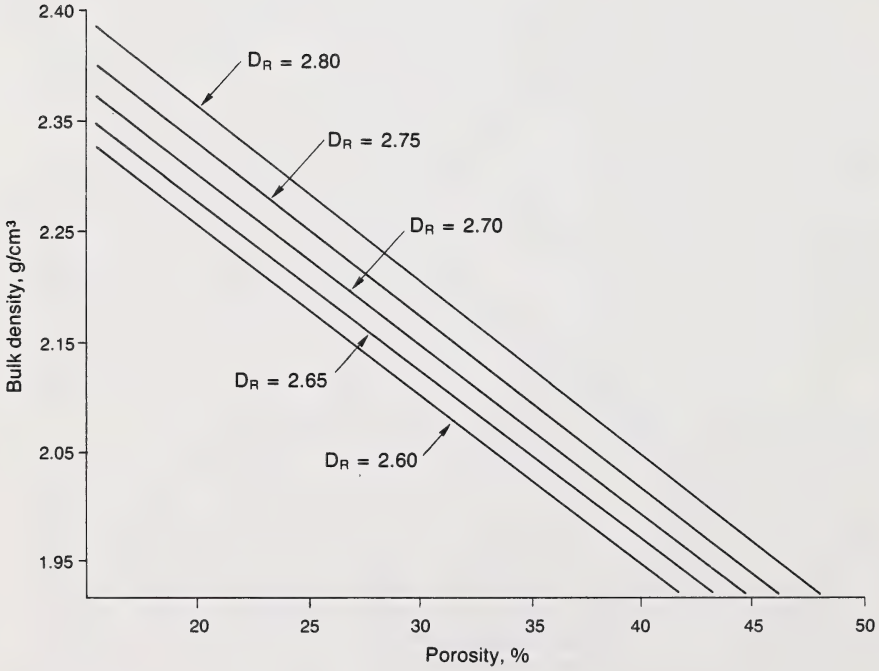

Figure 6. Saturated bulk density and porosity as functions of mineral relative density.

3. DISCUSSION

3.1 CLASSIFICATION SYSTEM

3.1.1 Introduction

The proposed classification system that follows describes the transitional materials encountered in the Plains area of Alberta. The primary shortcomings of the present systems are that the influence of clay minerals and carbon content are not sufficiently recognized. Both factors can significantly affect the behavior of a material. As little as 8 to 10% (by mass) of a swelling clay such as smectite will dominate the behavior of a mine spoil and result in a great amount of swelling and slaking when the sample is exposed to water. Carbon, on the other hand, is a stable substance in the presence of water.

Physically, this classificatin system is only slightly more involved than systems presently employed. The system consists of five steps or observations as summarized in Table 1. A hydrometer analysis, a test already widely used, results in the quantification of the sand-silt-clay fractions in a sample. The moisture sensitivity, as defined by a swell-slake test, identifies the cohesiveness of a sample. The swell-slake test is not presently used in existing classification systems and is the main modification proposed. Visual observation will determine the shale fissility of a sample. X-ray diffraction, again a method often employed in classification systems, identifies the type and fractions of clay minerals found in the clay sized particles. Determination of the carbon content completes the identification process. These observations are then presented and allow classification of the material by the use of three ternary diagrams.

3.1.2 Grain Size Classification

The average grain size is used to give a first classification of a lithology. The commonly accepted limits for the

Table 1. Examples of proposed lithological classification system.

	Properties					Name
	Grain Size Analysis Percent Sand/Silt/Clay by Hydrometer on Mineral Matter	Moisture Sensitivity Disaggregates in Distilled Water	Presence of Shale Fissility	Clay Mineralogy Chlorite/Illite/ Kaolinite/Smectite Percent of -2 Microns	Carbon Content Percent by H_2O_2 Digestion	
1	55/5/40	Yes	-	Not done	>10%	Carbonaceous clayey sand
2	80/0/20	Yes	-	5/25/5/65	0	Smectitic sand
3	70/5/20	Yes	-	10/40/10/40	0	Smectitic clayey sand
4	80/0/20	No	-	10/80/0/10	0	Illitic sandstone or sandstone
5	10/40/50	No	Yes	-	-	Silty shale
6	10/40/50	Yes	Yes	-	-	Silty clay-shale
7	0/40/60	Yes	Yes	20/30/20/30	8% (black)	(Black) smectitic silty clay-shale
8	20/50/30	No	Yes	-	10%	Carbonaceous clayey siltstone
9	Not done (mostly silt and clay)	Yes	No	-	-	"Mudstone" or "Mudrock"
10	0/5/95	Yes	No	0/5/0/95	-	Bentonite
11	0/10/90	Yes	Yes	0/10/5/85	11%	Carbonaceous smectitic clay/shale
12	5/30/65	No	No	-	-	Silty claystone
13	30/30/40	No	No	-	-	No suitable name as yet, perhaps sand/silt/claystone
14	25/15/60	Yes	Yes	5/25/10/60	>10%	Carbonaceous smectitic, sandy clay-shale
15	10/75/15	Yes	No	5/40/5/50	>10%	Carbonaceous silt
16	10/10/80	-	Yes	-	60%	Clayey coal or shaley coal
17	0/5/95	-	-	0/10/0/90	80%	Smectitic coal
18	20/20/60	-	-	5/5/0/90	70%	Smectitic clayey coal

grain size categories are: greater than 60 microns for sands, 2 to 60 microns for silt sizes, and less than 2 microns for clays. These limits contain no component of mineralogy or behavior and are defined solely on the basis of a sieve and hydrometer analysis, providing the materials can be totally disaggregated, which is usually the case for all materials except carbonaceous shales, cemented sandstones, and coal. The standard techniques for sample disaggregation may not be satisfactory for the over-compacted Cretaceous and Tertiary bedrocks. Techniques using a blender for full disaggregation should be employed. The use of H_2O_2 to break apart carbonaceous clays and shales likely results in some breakdown of clay particles, and ignition to remove carbon or organic components causes irreversible degradation of clays and creates agglomerates which cannot be dispersed. Removal of carbon is intended to aid grain size analysis. Index tests on clean mineral matter do not reflect expected behavior. A gentler extraction technique, such as using permanganate, is advised if highly accurate work is necessary. In dispersing materials for hydrometer analysis or elutriation, a dispersant such as sodium hexametaphosphate should always be used as the salinity of many of the bedrocks can lead to flocculation in the hydrometer cylinders. Calculations are carefully corrected to account for the presence of the dispersant.

The hydrometer analysis yields a measure of clay sizes content (less than 2 microns) which is purely empirical because the technique measures the effective (or equivalent) spherical settling diameter. The clay mineral particles may have long axis measurements well in excess of the 2-micron limit, but they settle much more slowly than a spherical particle. Consequently, some of the clay minerals settle in the silt sizes fraction, and, conversely, the clay sizes fraction contains some proportion of nonclay minerals. Empirically, the procedure is valid as the errors tend to be compensating, and the measure of clay sizes is assumed to be a valid measure of total clay mineral content. The empirical nature of the measure must always be acknowledged. It is not valuable to pursue

other, more expensive means of clay content determination. Scanning electron microscopy techniques may be used to give a visual semi-quantitative assessment of the efficacy of separation into clay and nonclay fractions, but is severely limited in this area, except as a research tool.

The average grain size gives the gross category of a material, and a qualifying adjective is affixed to indicate the secondary content. There is still some debate over what the numerical values of the grain size categories should be in order to affix the qualifying adjective. This is quite important in the cases of sands and silts with appreciable quantities of smectite, as this material has a large effect on behavior. The systematic use of a ternary diagram is recommended despite the difficulty with the smectite component. A widely accepted classification diagram is presented as Figure 7 (Shepard 1954).

3.1.3 State of Cementation and Degree of Over Compaction

Affixing "-stone" to the grain size group name is a contentious issue as, in some cases, it is assumed that such a material has a stress-independent cohesion or cementation, which is not usually the case in these materials. One interesting consequence of this research is that it is clear that differentiation between "sands" and "sandstones" or between "silts" and "siltstones" is quite feasible based on the tendency to disaggregate in water. We recommend that materials that disaggregate not have the suffix "stone" added, and materials that do not disaggregate be referred to as "sandstones", "siltstones", or "claystones". The recommended criterion is that adding the prefix "-stone" be done only when specimens display less than 25% swelling or slaking in a 24-hour test period in distilled water.

Use of the terms "mudstone", "clay shale", or "shale" is also a contentious issue. Some of the materials encountered do display a fissility, most do not. The usage of the AGI Glossary of Geology is recommended: "...a shale is characterized by finely

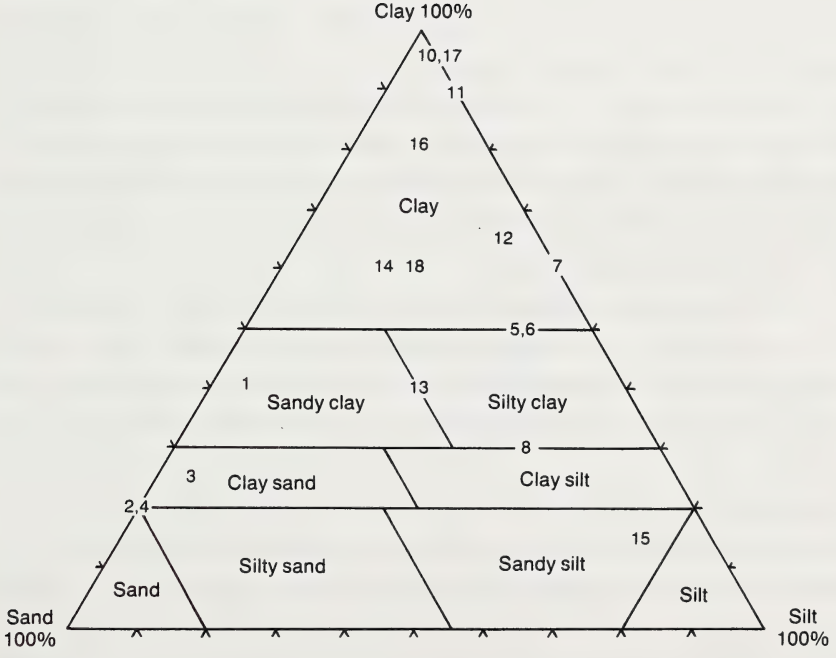

Figure 7. Widely accepted classification diagram (Shepard 1954).

stratified structure and/or fissility...". Also "Shale is generally soft but sufficiently indurated so that it will not fall apart on wetting..." (AGI 1974, pp. 650-51). Materials that swell and slake to a high degree within a set time (8 h or 24 h) are not to be called shales. The use of the term "clay shale" has also been extensively debated because of different interpretations. Its use is so wide, particularly in western North America, that it will probably remain in use. The usage recommended, and the one most widely accepted, is for a material with fissility but which reverts to a clay upon weathering. The latter criterion could be redefined in terms of the swell-slake test to a material which swells or slakes on exposure to fresh water. In accordance with these comments, a "clay" has no fissility and disaggregates in water, a "clay shale" has fissility and disaggregates, and a "shale" has fissility but does not break up in water. The term "mudstone" may be used only when the specific proportions of clay and silt sizes are unknown and the material has no fissility. As such it is a group name rather than a specific lithological category such as clay or clayey silt. Other terms, such as "compaction shale" (Locker 1973) or "mudrock", are not necessary in this classification scheme.

There is some difficulty in the degree of over compaction implied by the use of the terms clay shale or claystone. It is felt that the degree of over compaction of transitional materials such as Plains sediments can best be described by the liquidity index, which is a measure of the in situ water content expressed as a function of the liquid and plastic limits. Negative values for near-surface materials always implies over compaction. The water content is preferably obtained from back calculation from a density log.

3.1.4 Clay Mineralogy in Lithological Descriptions

The development of a behavior oriented lithological categorization for clay-rich materials is more difficult because the clay content tends to dominate behavior if more than 25% (by mass) of the rock is clay. If a sand or silt contains more than 25% clay

mineral, it is suggested that the prefix "clayey" be added. The ternary diagram presented in Figure 8 should be adhered to.

If a lithology has enough of a single component to be called a "sand" or "silt", but contains more than 10% smectite, it is considered worthwhile to include the prefix "smectitic", as even low percentages of this mineral have an impact on material behavior. Hence a "smectitic sand" has at least 75% sand sizes, but contains between 10 and 25% smectite. Affixing the term "smectitic" when the smectite content is in excess of 40% of the clay mineral will allow a valuable behavioral assessment to be made from a laboratory derived lithological description. A "smectitic clayey sand" would contain, in general, at least 50% sand sizes and more than 25% clay sizes of which 40% would be smectite (that is, greater than 10% total smectite content). The material disaggregates in water therefore the name "stone" is not affixed. Thus, using the terminology developed to this point, a "smectitic silty clay shale" is a material that disaggregates in fresh water, falls in the appropriate "box" in the ternary diagram and therefore has a significant component of silt sizes, shows shale fissility, and has more than 40% of its clay content as smectite (at least 0.40 x 0.50 = 20% of total dry weight is smectite, in this case). The classification system requires only a grain size analysis, a static swell-slake test, and a semi-quantitative clay mineral X-ray diffraction analysis (Dusseault and Scafe 1978, 1982). Only the swell-slake test is added, the other two are commonly performed analyses.

The term "bentonitic", as in "bentonitic sandstone", is still found in the literature. Bentonite is a rock-type name and has genetic implications. Its proper use is to describe only beds of a volcanic origin dominated by the smectitic clay mineralogy (AGI 1974). The use of the term "smectitic" is greatly preferred as it is a rigorous mineralogical description with no genetic implications. Use of the term "montmorillonitic" is reserved for cases where that particular smectite specie has been rigorously determined.

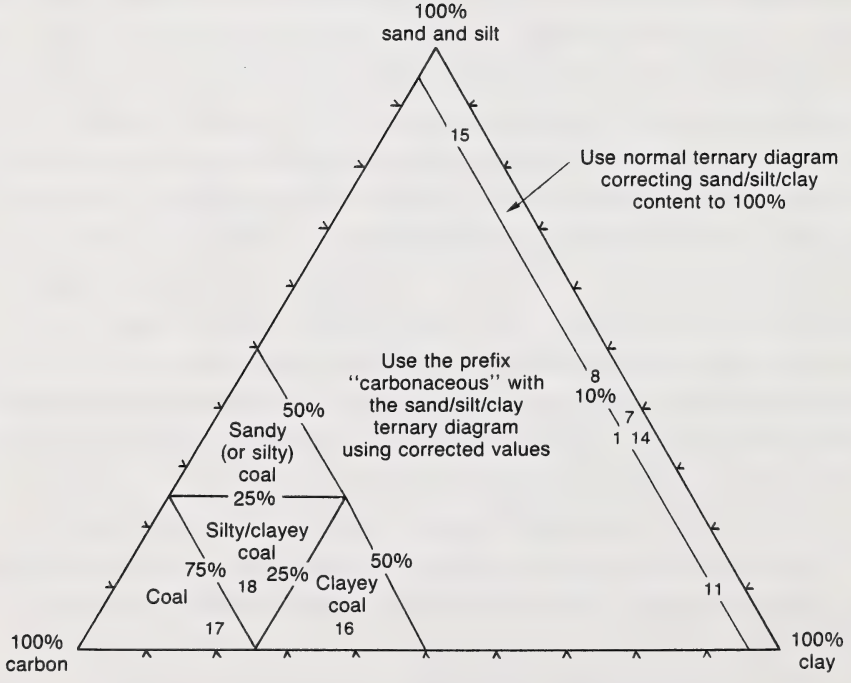

Figure 8. Modified ternary diagram for clay minerals.

The major division among clay species for engineering purposes is between swelling and nonswelling clays. As all common free swelling clays are smectite group members, this descriptive technique also contains a useful implication of swelling behavior. The other two most common clay groups in Cretaceous and Tertiary rocks of the Plains region are the illite group and the kaolinite group; chlorite is uncommon and vermiculite is extremely rare. For the Plains region, a ternary diagram for clays is satisfactory, as chlorite and kaolinite may be lumped for graphical purposes as shown in Figure 8. For the foothills region, the use of a four-axis diagram (rhomb diagram) including chlorite as a separate axis may be useful (Figure 9).

3.1.5 Lithological Usage for Carbon Content

The final major lithological component that seems to have important behavioral consequences is carbon. Small amounts of comminuted carbon can make a clay quite black, but have little effect on plasticity behavior after the material is disaggregated. On the other hand, quantities of carbon seems to affect the swell-slake behavior, making the materials much less susceptible to water. The AGI Glossary of Geology (1974) does not quantify the meaning of the term "carbonaceous". The usage proposed, because it seems to be a behaviorally useful measure, is that any material containing greater than 10% free carbon be called a "carbonaceous" material. If the content is greater than 50% free carbon, it should then be called a coal, with appropriate qualifying terms such as a smectitic clayey coal for a material containing more than 25% clay, more than 50% free carbon, and with the clay minerals being comprised of at least 40% smectite. A carbonaceous silty clay would be a material dominated by clay sizes, containing at least 25% silt sizes, and containing at least 10% carbon.

Some difficulty may arise in classifying materials with equal quantities of clay, sand, silt, and carbon, as carbon is a mineral component, not a grain-size component. Using a modified

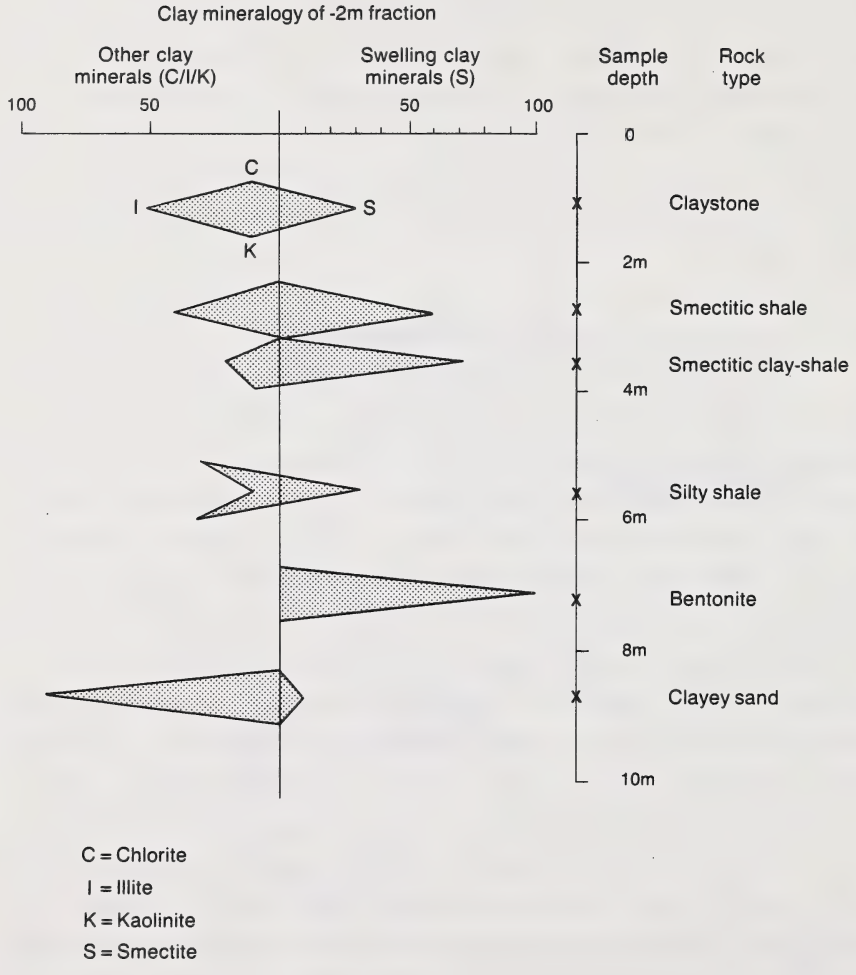

Figure 9. Rhomb method of plotting clay speciation versus depth.

ternary diagram plotting sand and silt together with coal as the third axis is a viable method, or the grain sizes of the noncoal minerals may be used alone as the major categorization. Neither of these methods is entirely satisfactory. Figure 10 gives suggested names for several material categories. Table 1 gives typical names derived from this geological engineering lithological descriptive scheme along with the limits that the names imply. The grain sizes are plotted on Figure 7. An attempt has been made to illustrate some typical lithological classifications on these diagrams.

3.1.6 Recommendation for a Lithological Classification System

The adoption of a formal descriptive handbook describing the soils according to clay type and content as well as carbon content is recommended to serve the purposes of both geologists and engineers.

3.2 THE USE OF GEOPHYSICAL LOGS

3.2.1 Introduction

Geophysical logs are extremely useful for inter-well correlation and determination of intact porosity. They are also useful for identification of distinctly different lithologies such as coal, clean sand, cemented siltstones, and even, to some degree, carbonaceous clays. They are much less useful in distinguishing among dirty or clayey sands, smectitic clays, clayey silts, and well-graded mixtures of these beds. Geophysical logs are of little use in direct determination of geomechanical behavior, but may have some use in correlating between properties and lithologies, as well as between behavior and facies.

3.2.2 Porosity and Bulk Density

From the data on lithological descriptions and from the natural water contents the porosity ranges for the materials encountered have been determined and are contained in Table 2. The following is a summary of this table:

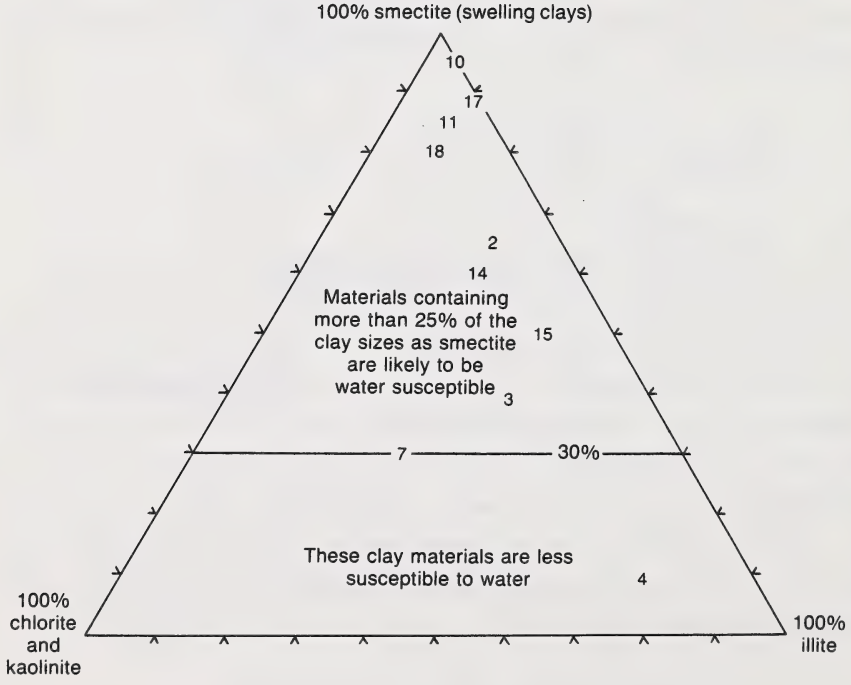

Figure 10. Modified ternary diagram including carbon content.

Table 2. Calculated porosities.

Depth	Description	Porosity	Depth	Description	Porosity
	Hole # PHRP 5-2			Hole # PHRP 6-3	
1.35	shale	38.2	2.44	clay	41.2
2.74	shale	35.6	4.76	coal-shale	43.1
3.45	siltstone	33.4	5.78	mudstone	40.1
3.64	sandstone	32.4	5.89	shale	37.6
4.88	mudstone	38.6	9.24	shale	44.8
5.50	shale	34.3	10.03	sandstone	32.2
7.25	shale	31.2	10.58	coal-shale	40.3
7.89	siltstone	31.0	16.25	shale	32.5
12.03	mudstone	27.4	17.42	sandstone	28.0
15.13	shale	59.4	18.51	shale	43.6
			21.95	coal-shale	36.4
	Hole # PHRP 23-3			Hole # PHRP 24-2	
5.93	till	33.9	7.01	shale	34.0
8.39	sandstone	32.2	7.56	sandstone	31.6
11.95	clay	36.4	7.97	siltstone	38.4
13.17	sandstone	37.9	9.08	siltstone	36.3
16.45	mudstone	36.4	12.66	shale	43.0
17.46	mudstone	40.7	13.72	shale	34.0
19.04	sandstone	26.9	14.34	sandstone	38.3
20.44	shale	52.6	14.59	shale	32.8
23.25	shale	40.5	15.85	siltstone	26.8
24.84	sandstone	--	17.65	shale	23.8
26.01	sandstone	14.6	19.51	sandstone	25.5
			22.18	shale	21.9
	Hole # PHRP 10-2		23.98	coal-shale	38.0
3.92	sandstone	34.6	26.03	siltstone	58.3
9.55	sandstone	49.3	28.60	shale	33.1
10.35	shale	53.4	29.86	coal-shale	31.9
16.14	shale	39.2	30.02	sandstone	18.8

1. Materials classified as sandstones have porosities ranging from 25.5 to 38.3%, with one outlier in excess of 41%, likely in error. The average porosity is calculated as 30.2%.
2. Materials reported as mudstones or clay shales have a porosity range of 27.4 to 44.8%, with three outliers having values in excess of 51%. The average porosity is 37%.
3. Insufficient data exist for accurate determination of siltstone values, but a range of porosities of 26.5 to 43% is appropriate. The average value is intermediate to those of materials called sandstones or mudstones and clay shales.

The question arises as to whether these results are reliable. The judgement of the authors is that the wide range of porosities does not accurately reflect the in situ porosity because the swelling clays imbibe water during coring and also after coring when the materials are stored in their rubber sleeves or plastic liners with some drilling mud around them. Any imbibition of water leads to an overestimate of porosity, therefore the values reported represent maximum values; the actual values are lower.

An attempt to relate the lithological description to the porosity based only on the water content was unsuccessful. There is too much variation of material properties and clay speciation to justify any such relationship. Therefore, the use of porosity alone is not valuable. Figure 11 is a plot showing the relation of described lithology to the calculated porosity.

The bulk density data on geophysical logs were used in a different manner to calculate typical porosities of two major lithological subdivisions: sandstones and clay shales. The criterion to define the two was based on the Natural Gamma Ray data (accepting the previously mentioned limitations of this measure). A clay shale was arbitrarily defined as having a gamma ray value of greater than 105 API units, a sandstone as having less than 80 API

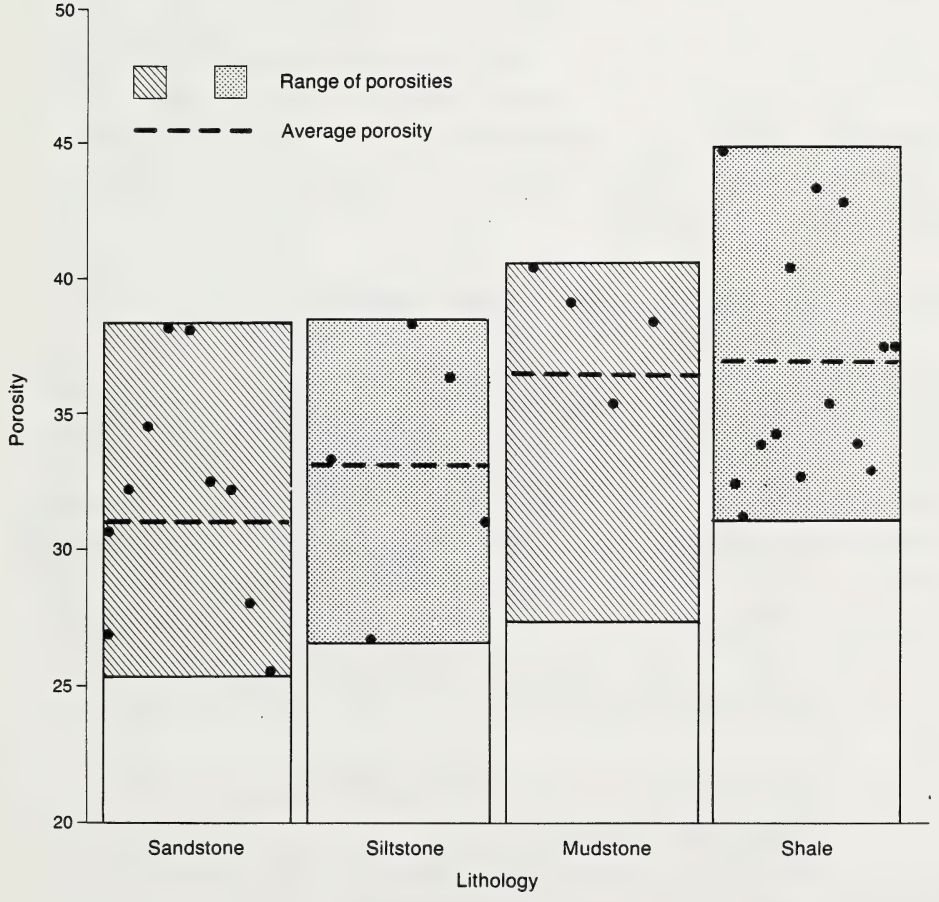

Figure 11. Relationship of described lithology to calculated porosity.

units natural radioactivity. An assumption of relative density for the shales of 2.75 and for the sandstones of 2.67 was made. The corresponding bulk density range was determined from the bulk density geophysical log and the porosities were back calculated. The results appear in Table 2. Unfortunately, no correction can be made for carbon content, which tends to reduce both the bulk density and relative density, giving a higher porosity value in carbonaceous clay shales. The table gives more reasonable data for porosity in situ. For example, a range of clay shale porosity of 19.5 to 42% is indicated. Although this method has its limitations, it is more reliable for use in carbon-free materials providing that the bulk density data are reliable.

3.2.3 Relationship to Geophysical Properties

Several plots attempting to relate the index properties to the geophysical measurements were made (Figures 12 to 15). The one relationship which can be postulated is that the plasticity index is related to the Natural Gamma Ray radioactivity log, which is of course related to the lithology. This is not a startling conclusion; clay shales in general give a higher gamma response and are also more plastic. The bulk density log yields no significant relationships except that low density clays are carbon-rich, and are also less plastic and more stable in water. These topics are discussed at greater length in other places in this report.

3.2.4 Recommendation for the Use of Geophysical Logs for Geotechnical Purposes

Because of the problem of sample disturbance, systematic use of the geophysical data to compute in situ porosities is recommended. Care must be taken to ensure high-quality boring so that the data are accurate. The technique requires that a mineral relative density be determined. In the absence of such an analysis, assumed values may be used only if carbon or coaly matter is absent. The strongly swelling nature of the smectitic mudstones of the Plains

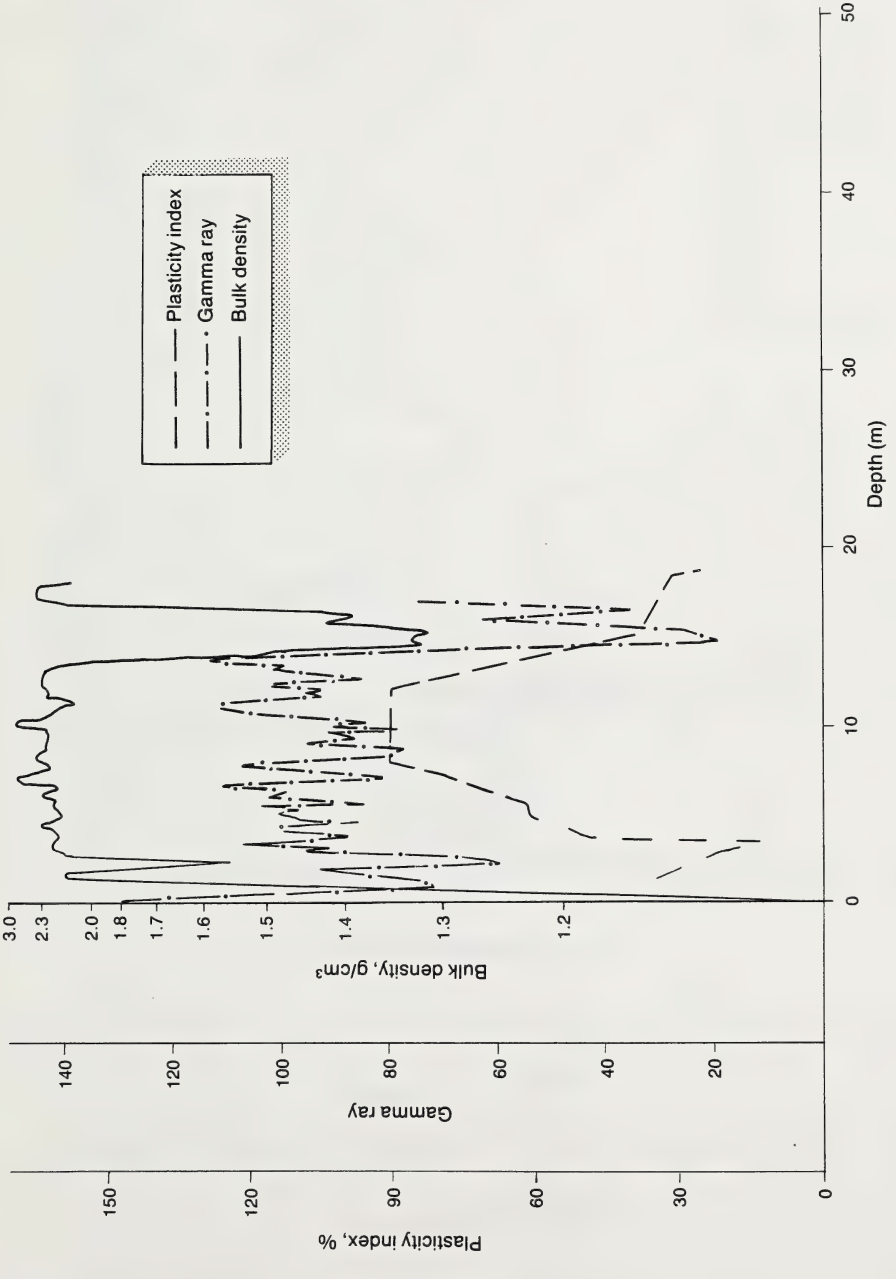

Figure 12. Correlation of bulk density and gamma ray logs with plasticity index for PHRP 5-2.

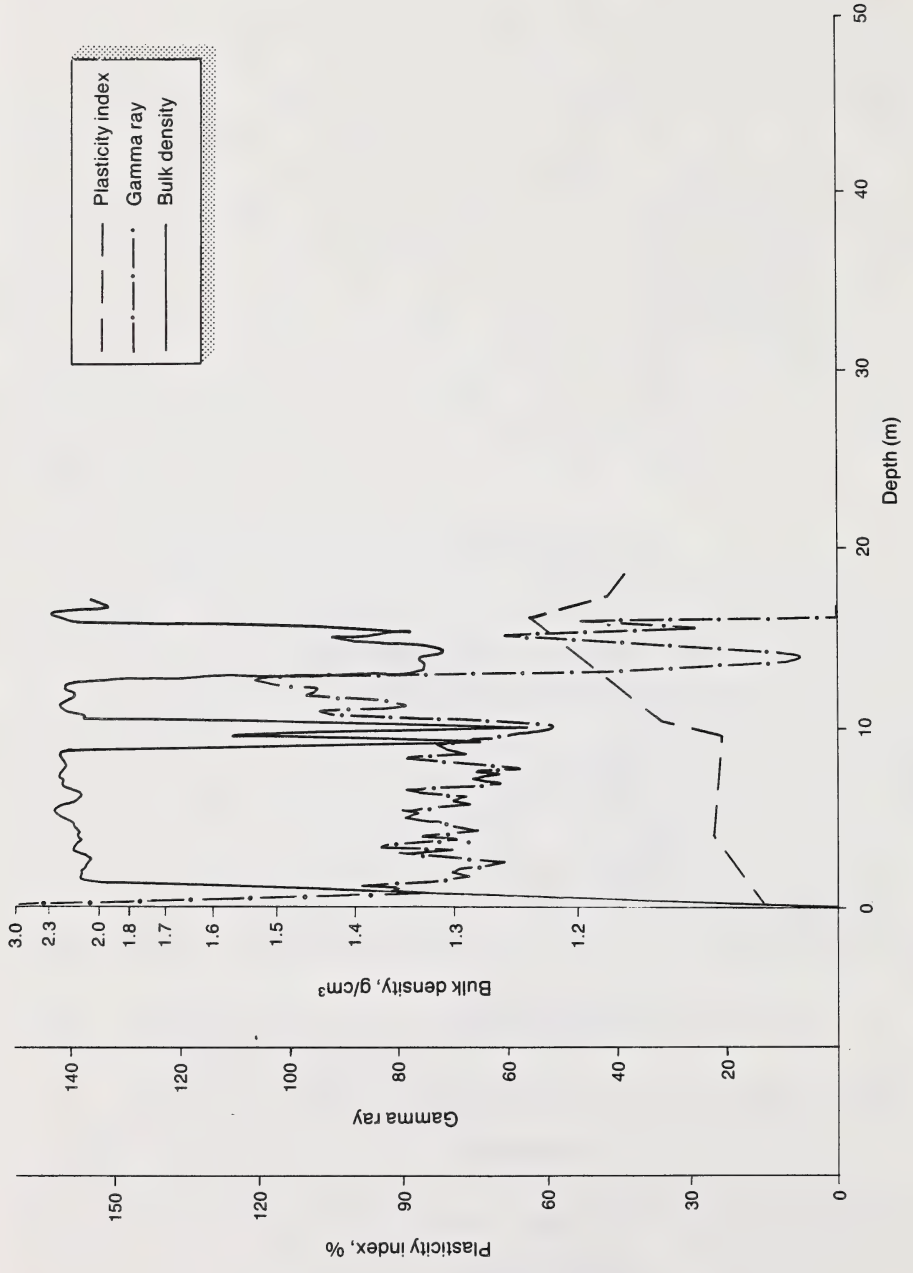

Figure 13. Correlation of bulk density and gamma ray logs with plasticity index for PHRP 10-2.

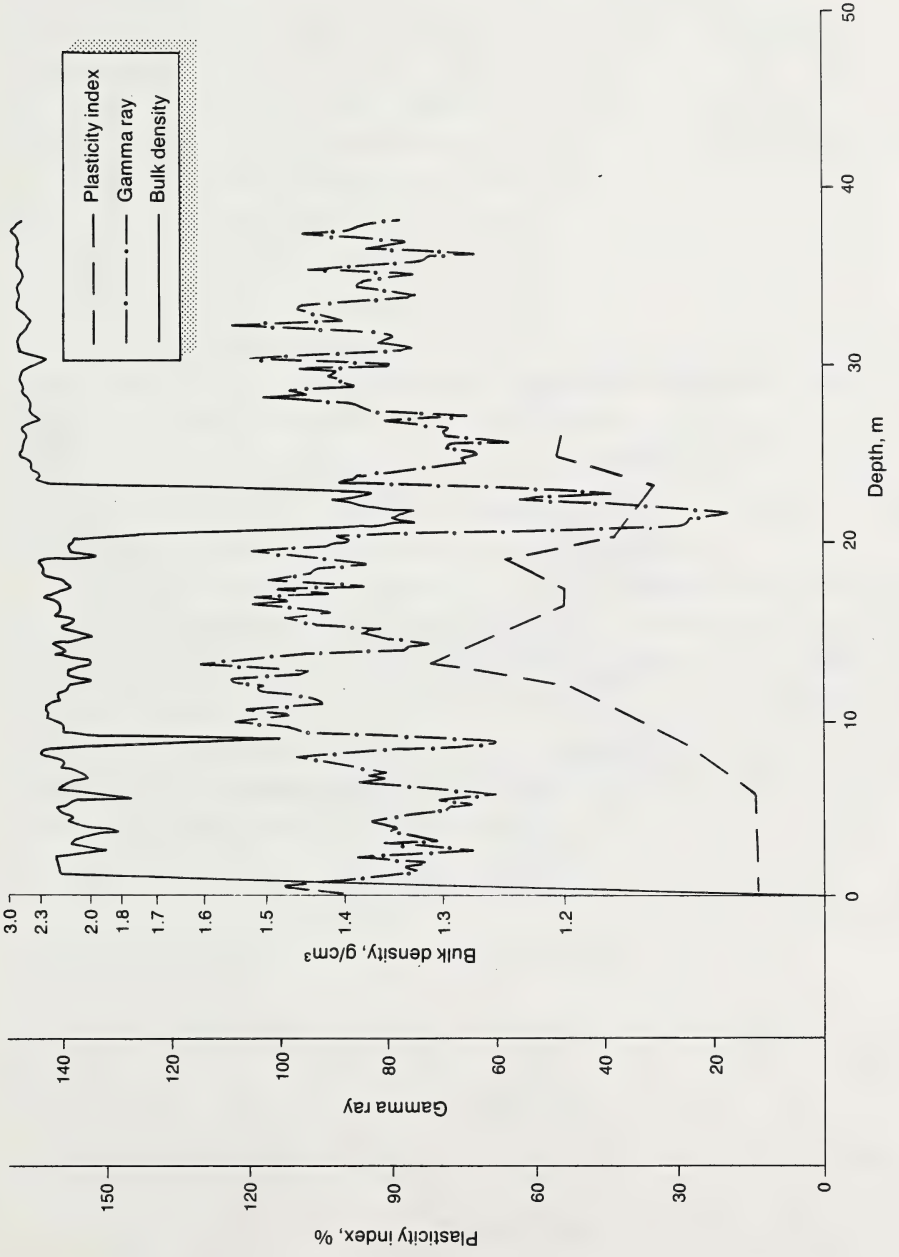

Figure 14. Correlation of bulk density and gamma ray logs with plasticity index for PHRP 23-3.

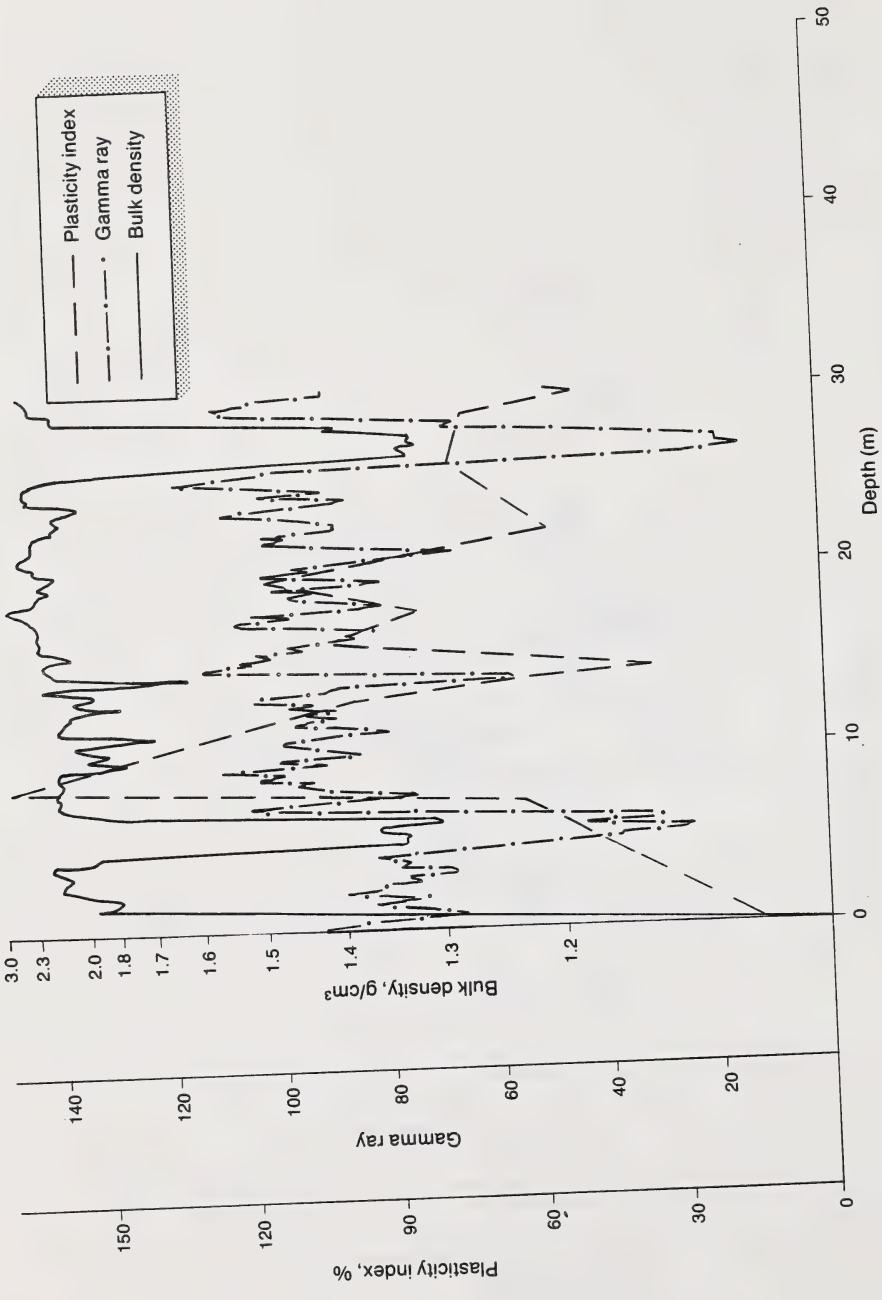

Figure 15. Correlation of bulk density and gamma ray logs with plasticity index for PHRP 24-2.

region suggests that drilling with a KCl base drilling fluid could recover superior core samples, and this technique is advised if reliance is to be placed on core data rather than log data.

The use of natural radioactivity logs for gross lithological division is recommended, but the logs must be calibrated to core observations backed up by laboratory analyses. Differentiation among mudstone lithologies is probably impossible using geophysical logs. Identification of cemented siltstones by using density data is strongly recommended.

The greatest power of geophysical logs is in correlative facies study. Since the engineering properties are usually related to the lithofacies, if continuity of a particular lithology can be established by geophysical techniques, there is an extremely high probability that behavioral assumptions can also be extended, reducing the quantity of laboratory analyses required.

The site-specific nature of the correlations extracted from logs must be emphasized; also, the utility of these devices increases as the experience of the interpreter develops. The development of a handbook of guidelines oriented to the site industrial geologist and engineer for the uses and limitations of geophysical logs for geomechanical purposes should be pursued. Such a document would be valuable to industry and research agencies alike.

4. CONCLUSIONS

The major conclusions and recommendations of this report are listed below.

1. A major study integrating clay mineralogy, engineering behavior, lithological descriptions, laboratory methods, and the use of geophysical logs should be initiated. The data from the Forestburg project will serve as the base for this study, however, at least one other site should be studied in similar detail to provide a comparative data base.
2. An investigatory group to standardize laboratory methods for Plains transitional materials should be started. This group should contain engineers as well as soil scientists and geologists. It should be prepared to make recommendations to the Geological Survey of Canada, the Canadian Geotechnical Society, and other groups with interest. Perhaps the committee should be constituted under the auspices of these groups.
3. There are now sufficient data to warrant standardizing the methods of lithologic identification and classification. Many ambiguous terms should be dropped or carefully defined; some new terms are worthy of inclusion providing the implications are well understood. A published handbook is strongly recommended.
4. The use of geophysical logs in geomechanics and geology of transitional materials is sufficiently advanced that a handbook of methods and applications should be prepared for exploratory and industrial geologists and engineers working in transitional strata.

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